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The present study is concerned with production, transport and deposition of gravel in fluvial systems in hot arid regions. It attempts a definition of the variables affecting gravel origin, transport and deposition, assessment of significant changes in texture after deposition and evaluation of the composition of gravel buried in the upper alluvial section of depositional basins. The arid gemorphic environment is characterized by low precipitation, low rates of chemical weathering in most lithologic environments, high rates of mechanical weathering, scant vegetation and slow and sporadic soil development. General

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climate-process framework places most hot deserts in regions receiving less than 150 mm/yr of mean annual precipitation. Major geomorphic processes and events, occurring in rocky deserts are: mechanical weathering; debris flows and wash on hillslopes; free wind activity, precipitation of salts in fractured and elastic rocks and soils, and floods. Differential areal geomorphic activity and differential runoff-sediment contribution are very strongly emphasized in the arid environment.

ORIGIN AND DISTRIBUTION OF GRAVEL IN STREAM SYSTEMS OF ARID REGIONS

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ORIGIN AND DISTRIBUTION OF GRAVEL IN STREAM

SYSTEMS OF ARID REGIONS

TABLE OF CONTENTS

ILLUSTRATIONS

TABLES

LIST OF APPENDICES

(VOLUME II)

1.0 INTRODUCTION by Ran Gerson

1.1 OBJECTIVES OF STUDY

The present study is concerned mainly with the transport and deposition of gravel in arid regions. It was conducted with several objectives in mind:

1. Definition of those variables conducive to origin, transport and deposition of gravel in fluvial systems.
2. Assessment of the impact of aridity on fluvial systems.
3. Evaluation of the significance of addition and alteration of gravel by some external systems, namely eolian and pedogenic.
4. Development of a procedure to predict the composition of fluvial deposits in the upper alluvial fill of depositional basins.
5. Evaluation of the impact of high magnitude (extreme, "catastrophic") events on fluvial systems, and especially in their depositional environments.
6. Consideration of the influence of climatic changes and tectonic activity on the fluvial systems in arid regions.

1.2 SCOPE

The present study deals with fluvial systems that consist largely of streams that drain bedrock source areas and emerge from well-defined topographic fronts into the adjacent depositional basins.

Such fluvial systems are characteristic of the arid regions of the Basin and Range Province of southwestern United States. The climatic environment is a hot desert, with less than 150 mm of mean annual precipitation, no significant present-day role of chemical weathering in most lithologic

surroundings and no important effects of cold weather conditions. In the past (late Quaternary), however, the climate may have been significantly wetter and its effects are reflected in the stratigraphy of the basin deposits.

Under these conditions, the main output of sediment from most igneous, metamorphic and sedimentary lithologic environments is of gravel-through-boulder class sizes. Only in certain lithologic environments, such as shales and friable sandstones, is grain size readily predicted. In most others, no advanced study has been published for the arid environment.

A thorough search of the literature again leads to the persistent fact that no comprehensive study of the mechanics of gravel transport is available to date. Hence, it is essential to have in the present report a critical discussion of the knowledge on gravel transport and its interrelationships with erodibility, sorting and abrasion of coarse-grained sediments. Chapter 4 is devoted to both the general considerations and to the results of the present study regarding production, transport and deposition of gravel in arid fluvial systems.

Most subtropical hot deserts were affected by past climates that were significantly different from present climates. Wetter modes of geomorphic operation were active in the late Quaternary, in southwestern United States (Bull, in preparation), the Sahara (Rognon, 1967) and southern Israel-Sinai Peninsula (Gerson and Yair, 1974; Bull and Schick, 1979). These effects are best seen in the depositional basin. Chapter 5 and Appendix E illustrate the changes in basin fill related to different climatic regimes.

Even a casual inspection of alluvial basin fill in hot arid environments illustrates that some modifications have occurred either while the fluvial sediment was deposited or at a later stage. These modifications, either by additional eolian input or pedogenic alterations, are discussed in Chapter 6.

This report aims at a procedure to better understand and predict the composition in the upper portions of the alluvial deposits in well-defined deposition basins. Chapter 8 is devoted to this topic.

1.3 AVAILABLE MATERIAL AND DATA

As will be explained in later chapters (3.1), one may group the variables of the fluvial ecosystem under eight headings: 1. geology, 2. climate, 3. topography, 4. vegetation, 5. hydrology, 6. geomorphic processes, 7. hydraulic geometry, 8. sediment characteristics.

Only five of the above groups are readily available, but only in part: geology, climate (in a general way), topography, vegetation and sediment characteristics. 'Available' in the present context means that these variables may be obtained in a matter of weeks through months for most fluvial systems. Still, even after some considerable study, there will remain a substantial inaccessible portion; accurate figures for active tectonism, magnitude and frequency of precipitation events, sediment yield.

The other groups include variables for which we do not have enough data for almost all arid regions. These variables are the dynamic ones, grouped under hydrology, geomorphic processes, hydraulic geometry and, hence, we cannot utilize them as conducive for sediment characteristics predictions.

Readily available material and data, in written or published form are:

1. Topographic maps, generally of 1:250,000 and 1:62,500 scales. Only occasionally maps of 1:24,000 are available.
2. Air-photographic imagery, generally of 1:60,000 to 1:125,000 scales. For favorable areas, large scale imagery may be specially obtained in a matter of days.
3. Geologic mapping. Most of the southwestern United States is mapped in a reconnaissance fashion. Usually scales are smaller than 1:100,000 and lithologies and structures are only skeletally sketched. Areas of interest have to be mapped according to needs.
4. Climatic data. Among these, precipitation is the most important with respect to fluvial activity. For most arid regions, including southwestern United States, data for detailed analysis of frequency, magnitude, duration and distribution of rainfall eventsare still wanting. Where data are available, their relation to runoff events is completely unexplored. Exceptions are Walnut Gulch, in semiarid southeastern Arizona and Nahal (=wash) Yael in extremely arid southern Israel (on definition of aridity for the present report, see Chapter 3).
5. Detailed vegetation maps are not available for most arid regions. Characteristic scales are 1:250,000 to 1:100,000. The relation between vegetation and sediment characteristics (size and yield) are practically unstudied. Exceptions are Walnut Gulch (southeastern Arizona) and Sde Boker experimental watershed (southern Israel).
6. Hydrology. Infiltration and/or runoff. Studied only in three experimental areas - Walnut Gulch, Nahal Yael and Sde Boker. Projection of results to most other arid areas is still impossible. Only trends and general implications are feasible.

7. Geomorphic processes. These are known to a certain quantitative extent. But because of lack of observations and present-day rates of activity, one has to depend on principles and indirect evidence to draw some quantitative conclusions. More on this central topic in Chapter 4.
8. Hydraulic geometry is known to be related to sediment characteristics. Since discharge, a major independent variable, is not available for arid fluvial systems, most variables within this category are not systematically correlated.
9. Sediment characteristics are only partially available. Of these, sediment yield is missing for all arid watersheds and most semiarid ones. Size characteristics are more readily available, as described in detail in Chapter 4.

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2.0 GENERAL SETTING

2.1 CLIMATE - THE ARID GEOMORPHIC ENVIRONMENT by Ran Gerson

Arid regions are those in which potential moisture losses from evapotranspiration exceed incoming precipitation. Bare rock is exposed, mainly in the upper and middle portions of hillslopes on most hardrock lithologies. Only one quarter to one half of the hillslopes are usually covered by debris mantle (Figure 4.3). Vegetation in these areas is discontinuous, sparse or absent, and is restricted mainly to colluvial pasts of hillslopes and to stream courses.

A general subdivision of arid region may be to two types: "warm-winter deserts", with insignificant frost action, and "cold-winter deserts", with significant frost action (Mabbutt, 1977). Most morphogenetic classifications are based on climatic characteristics, notably mean annual rainfall and mean annual temperatures. These are chosen mainly because they are more available than other data, such as evaporation and transpiration. Examples are studied by Peltier (1950), Leopold et al. (1964) and Wilson (1969).

Arid regions, according to Peltier (1950), are those in which mean annual precipitation ranges between 0 to 375 mm and a mean annual temperature of 15° to $30^{\circ}C$. Wilson (1969) arrived at a different definition in which mean annual precipitation in arid regions may range between 0 and 300 mm, but mean annual temperatures may range between less than $(-)25^{\circ}C$ and $(+)32^{\circ}C$. The definitions presented by Peltier (1950) and Wilson (1969) are both based on climate-process relationships.

Following Wilson's framework and observations in arid and semiarid regions, we should focus our attention on the predominant geomorphic processes

typical to arid regions and then redefine the arid regions dealt with in the present report. The processes that control or dominate sediment production in arid regions in general are dependent on availability of materials and topography:

1. Mechanical weathering (chemical weathering usually is, at present, very minor).
2. Debris flows as a typical mass wasting agent; surface runoff as a major transporter of debris.
3. Free wind activity in both transport and deposition of fines and sand.
4. Only incipient or no soil forming processes.
5. Precipitation of salts in joints, incipient soils and playas.

Regions that are dominated by the above diversity of geomorphic processes are found in the southwestern United States, north Africa, southwest Asia, parts of Australia and southwest Africa. A combination of these processes would fit mainly regions in which mean annual precipitation does not exceed 150 to 200 mm in the warm-to-hot climatic regimes (such as southwest United States, north Africa, southwest Asia).

Variance in degree of activity of different processes would depend on lithology, structure, climate and morphometry of hills and streams. Examples are:

1. Lithology. Chemical weathering is more significant in coarse crystalline granites and quartz monzonites than in fine-grained rocks of the same composition or in many other, intermediate, basic or metamorphic rocks.

2. Structure. Rates of erosion and persistence of debris flows are higher in densely jointed or shattered rocks. They are also enhanced by the steep hillslopes that are characteristic of tectonically active terrains.
3. Climate. In southwestern United States, there is a marked difference in weathering and debris transportation between the more arid southwestern Arizona and the less arid and cooler Mojave Desert or central Nevada, where more precipitation and occasional freeze-thaw processes accelerate both chemical and mechanical weathering and transport of debris.

Climatic change, and transformation into a semiarid regime, may affect all facets of landscape:

1. More intensive and deep chemical weathering, producing smaller-sized clastics, causing higher sediment yields.
2. Wash processes on hillslopes assume a higher degree of relative importance; larger portions of hillslopes get covered by colluvium and vegetation; the access of wind to bare rock and exposed colluvium is diminished.
3. Higher rates of deposition of sands and fines in depositional basins.
4. Development of soil profiles, including a distinct argillic B horizon and higher rates of $CaCO_3$ precipitation as mottles and continuous gravel coatings.

Climatic change may cause a definite shift in process, related mainly to rock type. Granites, amphibolites, schists and indurated sandstones are more sensitive to climatic change and result in greater variations in sediment

yield than basalts, cherts and quartzites. Still, Quantitative data correlating rock composition, rock texture and climatic characteristics, are wanting. Because of lack of abundant moisture and differential mineral weathering, there is no general trend of degree of chemical weathering within the acid- to ultrabasic-based rock classifications. A better trend appears along the textural line, porphyritic through pegmatitic, the latter being more weatherable under most rock compositions.

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2.2 GEOLOGY by William B. Bull

The complex geology of southwestern Arizona has been mapped only in a reconnaissance fashion. Detailed investigations have been made locally where mineral deposits have warranted more intensive work. The first regional mapping was done by E. D. Wilson based on his field work done between 1929 and 1932 (Wilson, 1933). Later reconnaissance mapping by Wilson was included in his "Resume of the Geology of Arizona" published as Arizona Bureau of Mines Bulletin 171 in 1962. Southwestern Arizona lies in the central part of the southern Basin and Range Province (Figure 2:1). The area consists of widely spaced mountain ranges that trend toward the northwest. The following sections briefly summarize the morphology and structure of the mountain ranges, and the characteristics of the basin fill are discussed in detail in the later chapters.

2.2.1 LITHOLOGY

Most of the mountain ranges consist of granitic and metamorphic rocks (Figure 2:2), and the Gila, Sierra Pinta, Copper, and Mohawk mountains have extensive areas of both metamorphic and plutonic rocks. Sedimentary rocks are present only locally, such as at the north end of the Copper Mountains. Volcanic rocks are important in many of the ranges and overlie the gneissic and granitic complexes. Small outcrops of basalt occur as buttes, such as Ravine Butte in the Tinajas Altas Mountains. The Cabeza Prieta Mountains have extensive areas of andesitic rocks. The Aguila Mountains consist of a diversity of rock types that include basalt, andesite, rhyolite and tuffacious materials. Lava flows are also present in the Pinacate volcanic field where it extends across the border from

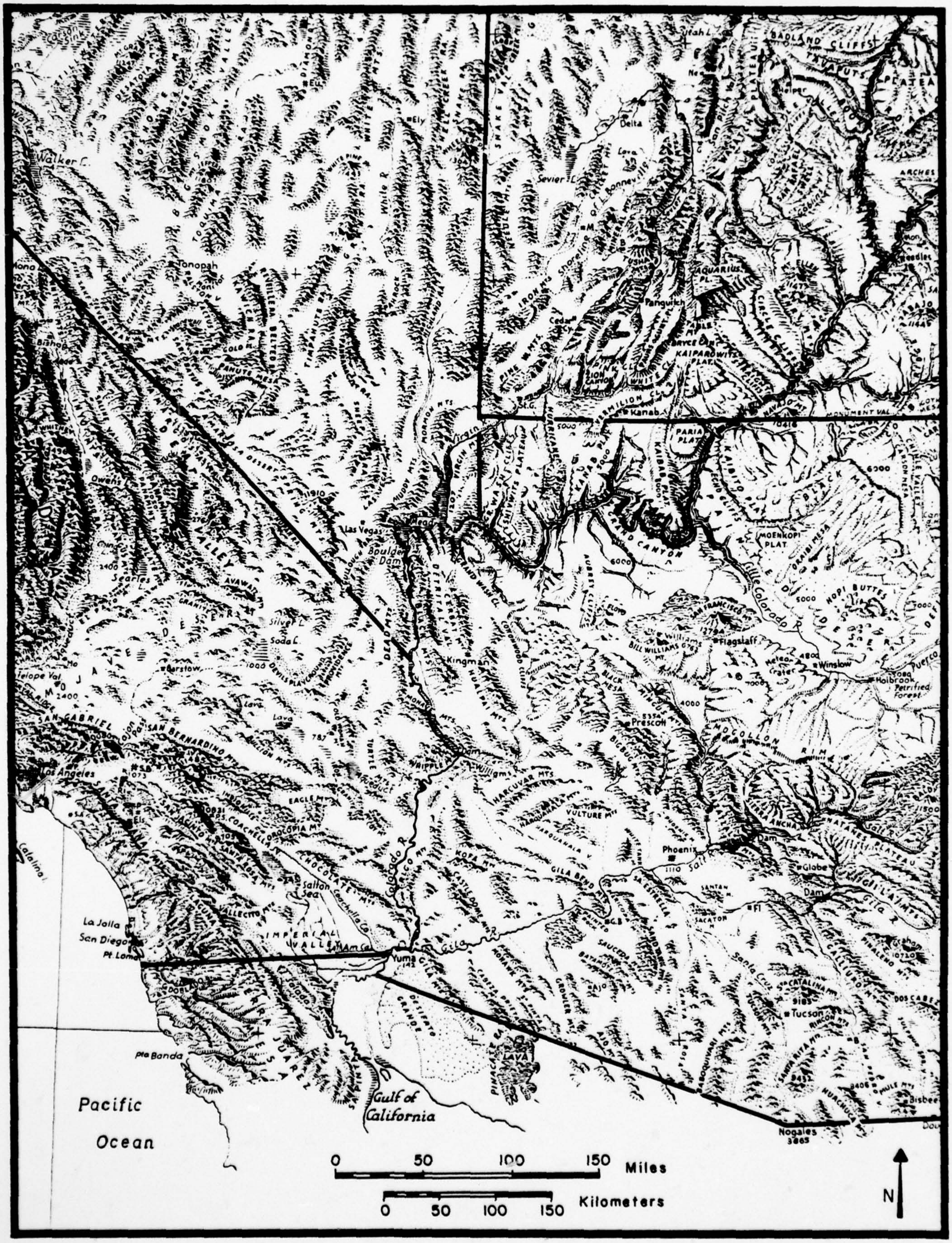


FIGURE 2:1 Basin and Range province (from Raisz, E. 1957).

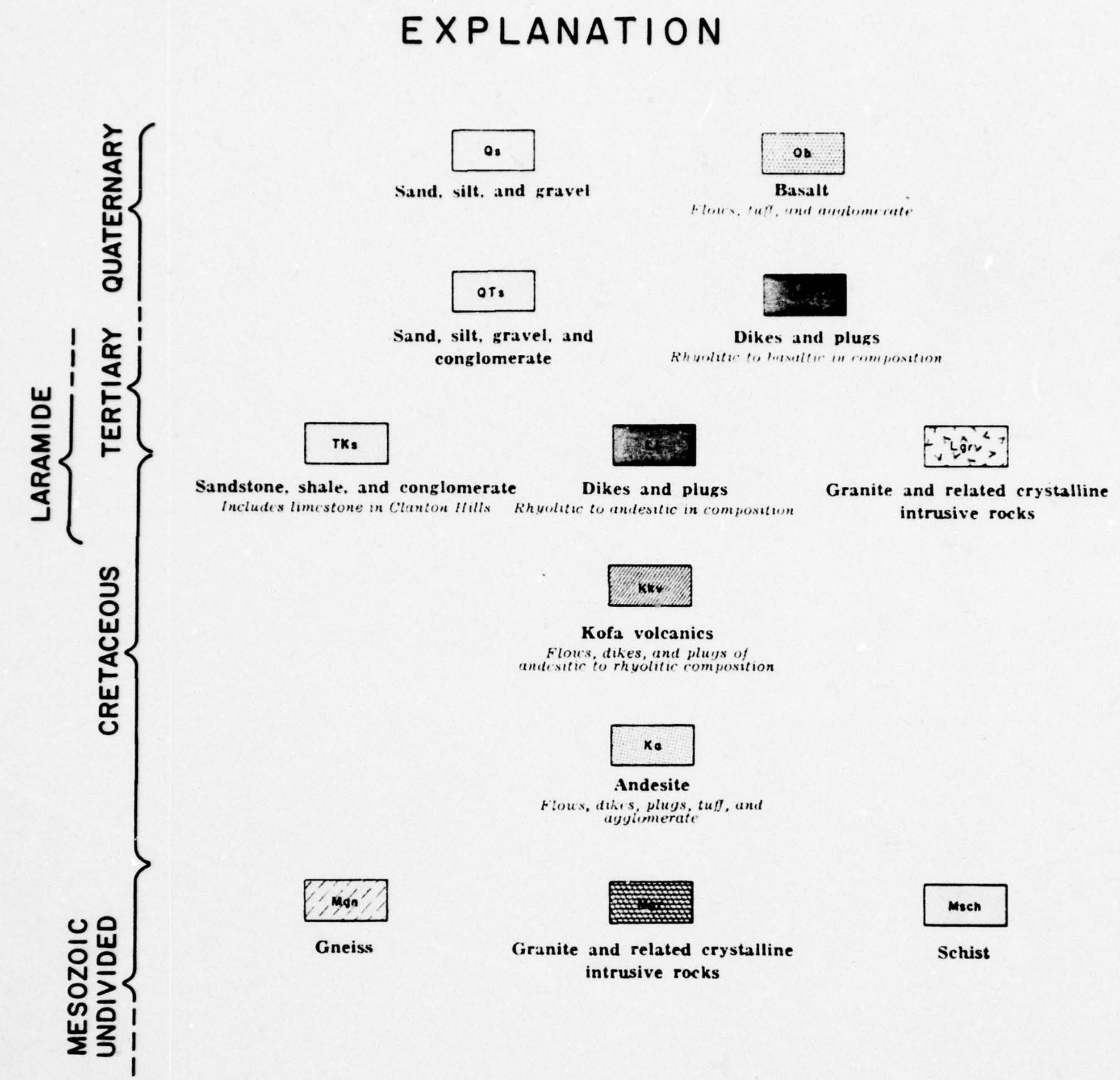
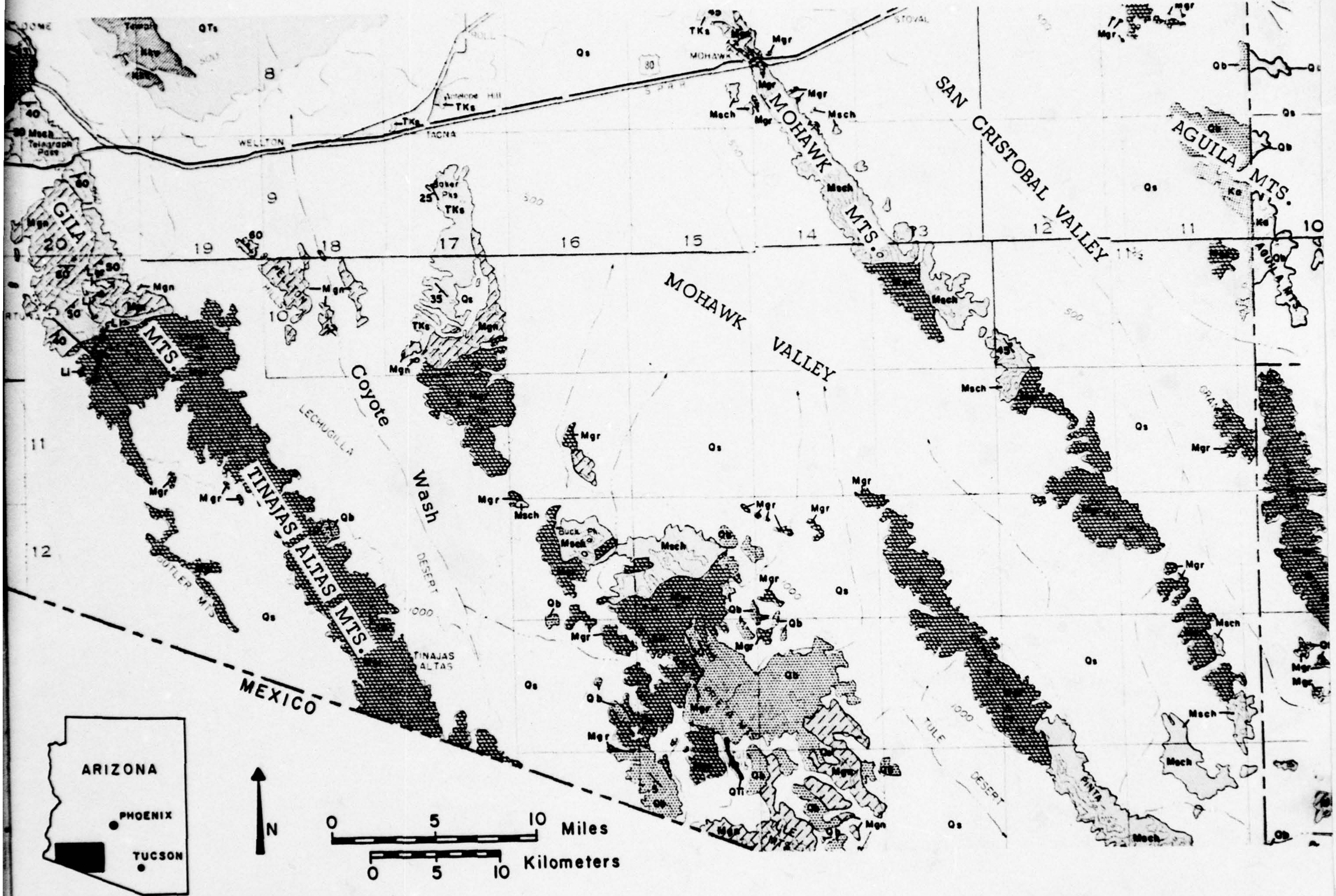


FIGURE 2:2 Geologic map of southwestern Arizona (from Wilson, E.D., 1960, Geologic map of Yuma County, Arizona Bureau of Mines).



GILA MTS.
TINAJAS ALTAS MTS.
MOHAWK MTS.
AGUILA MTS.
SAN CRISTOBAL VALLEY
MOHAWK VALLEY
Coyote Wash
LECHUGILLA DESERT
TULE DESERT
MEXICO
WELLTON
TACNA
MOHAWK
STOVAL
Telegraph Pass
ARIZONA
PHOENIX
TUCSON
N
0 5 10 Miles
0 5 10 Kilometers

Sonora, Mexico. The Sentinel volcanic field north of the Aguila Mountains is another extensive area of basaltic lava flows.

Potassium-argon dating, by Paul Damon of the University of Arizona, suggests that the ages of some of the units shown in Figure 2:2 should be revised. Some of the granitic intrusives may be originally Precambrian in age but have had their radiogenic clocks reset during Laramide time. The andesitic and rhyolitic flows and tuffs of the Cabeza Prieta area appear to be middle to late Tertiary in age rather than Cretaceous, and basaltic rocks, such as Ravine Butte, appear to be about 20 million years old. Both the Pinacate and Sentinel volcanic fields have lava flows that have been dated as being Pleistocene (less than 2 million years old).

2.2.2 STRUCTURE

The reconnaissance nature of the investigations that have been made in southwestern Arizona is revealed by the almost total lack of geologic structures on Figure 2:2. In part, this is the result of insufficient study, but in large part, it may be the result of burial of the range bounding faults by the alluvium in the basins. The structural situation appears to be dominated by northwest-striking faults that created the mountain ranges. Although normal faulting was responsible for the relief of the ranges, many of the faults may have a large, right lateral, strike-slip component. The time of major tectonism appears to have been during the mid-Tertiary, and downwasting of the mountain ranges has predominated since then. The erosional backwearing of the initial mountain fronts has resulted in the burial of the range bounding faults and in progressive narrowing of the mountain ranges. The typical subsurface expression for

ranges, such as the Mohawk Mountains, is shown diagrammatically by Figure 2:28 and Appendix I.

Other areas such as the Lechugilla Desert may have bedrock at shallow depths beneath the basin fill as is shown by the numerous outlyers of basement rocks between the Gila Mountains and the Copper Mountains. Each of the principle rock types in the study region has characteristic foliation and jointing which contribute to the characteristics of the sediment produced within a given fluvial system.

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2.2.3 TECTONIC ACTIVITY by William C. Tucker, Jr.

2.2.3.1 Introduction

Southwest Arizona has had a long history of tectonic and igneous activity. Large bodies of granite were intruded during the late Mesozoic which metamorphosed the pre-existing sediments and metamorphics. In the early to middle Tertiary violent volcanic eruptions poured out small, steep-sided flows of andesite and latite and blasted pyroclastic materials onto the adjacent landscape. A quieter phase of basaltic volcanism followed next and covered a wider area than the previous activity. Middle to late Tertiary high angle, normal faulting broke Southwest Arizona into horsts and grabens which resulted in linear, northwest-trending mountain ranges separated by broad, downfaulted basins. There were some minor basalt flows along some of these faults, apparently toward the end of the period of basin and range faulting. Additional basalt flows were poured out during the late Tertiary and into the Quaternary. These flows were widely separated and apparently unrelated by either location or orientation to the basin and range faulting.

The major portion of the basin and range tectonism can be dated with a fair degree of reliability using the volcanic rocks and their relationship to the faulting as a guide. Volcanic rocks that are clearly pre-faulting, being either ruptured by the basin and range faults or uplifted to form mountain ranges, or both, fall generally into the 12 to 30 million year age range (Eberly and Stanley, 1978). The volcanic rocks which are not uplifted and show no apparent evidence of faulting have ages from 3 to 1.75 million years in the Sentinel basalt flows (Eberly and Stanley, 1978) and from 1.0 million years to very recent in the Pinacate volcano field (Lynch, pers. comm., 1979).

This brackets the major, widespread, basin and range faulting fairly well as being within the 3 to 15 million year age range. However, the indicators for the cessation of regional faulting do not exclude the possibility that localized faulting removed from these volcanic time markers could have occurred later than approximately 3 million years before present.

The area of the Luke Air Force Range, which is the area being considered in this tectonic geomorphic analysis, has had five seismic events greater than magnitude 4 recorded in recent times. The dates, locations, and magnitudes are shown in Figure 2:3. The source of these recent events and the existence of surface ruptures are presently unknown, but their occurrence, together with the proximity of known active tectonism along the nearby San Andreas Fault/Salton Trough/Gulf of California rifting, provides evidence for the possibility of tectonic activity in the area.

Many variables act together to form arid fluvial systems. Tectonic activity is the trigger that sets off the independent variable of tectonic base level change. If tectonic activity causes a stream's base level to fall along part of its reach, it will erode more aggressively upstream from the point or points of ground rupture, will create fresh deposits of coarse clastics downstream from that point, and transport these coarser clastics a longer distance downstream than would otherwise be possible with all other independent variables being the same. The presence of tectonic activity has partly controlled sedimentation, both from the standpoint of particle sizes as well as their areal distribution.

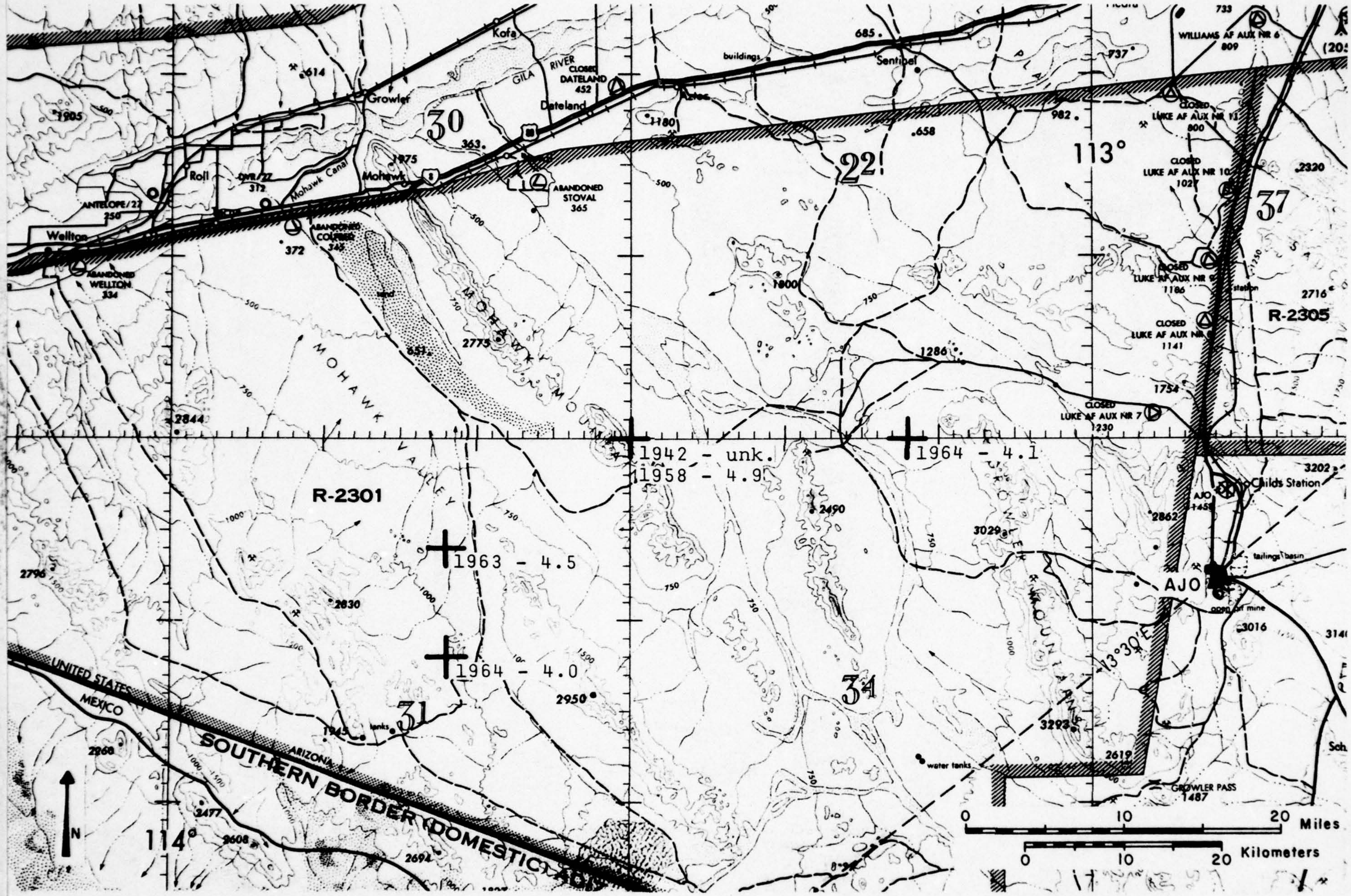

FIGURE 2:3 Recent seismic events within the Luke Air Force Range. Year and magnitude of the event is given at each approximate epicenter location. Source: Bureau of Reclamation, 1976. Scale: 1:500,000.

2.2.3.2 Purpose and Scope

This section of the report applies the concepts of tectonic geomorphology through landform analysis to assess the relative degrees of tectonic activity of mountain fronts or other structural elements during the Quaternary. The purposes of this section are to evaluate the areal variations in relative uplift of mountain fronts within the Luke Air Force Range portion of Southwest Arizona and to apply this evaluation of late Cenozoic tectonism of the area to determine its effect on the distribution and nature of fluvial sediments. The scope of this section includes (1) a discussion of the geomorphic parameters that are useful in defining relative rates of uplift, (2) a description of the mountain fronts in the study area and classification of them according to their late Cenozoic tectonic activity, and (3) a discussion of the impact of tectonic activity on the fluvial sedimentation in the study area. The analysis covers the entire 13,500 sq km (5,200 sq mi) area of the Luke Air Force Range.

The evaluation of past tectonic activity has two important applications to potential sites for MX trenches or silos. The first is seismic and the second is sedimentological. Wherever missile defense systems are constructed, it is essential that they not be placed across or adjacent to fault zones with a history of late Cenozoic ground rupture. This is especially important when one considers that the energy released by incoming nuclear warheads may release latent stresses along fault zones, thereby causing rupture of the defense facilities and rendering them inoperative. Tectonic geomorphic analysis has the potential for indicating which faults within a given study area have been active, including faults that have not been mapped by previous workers, thereby allowing comparison of potential seismic hazards between the numerous areas of being considered for MX missile defense

systems. Our study of the Luke Air Force Range shows it is a region of quite low seismic hazard. Our initial reconnaissance of the Nellis Air Force Range in southern Nevada suggests that it would have a much higher level of late Cenozoic tectonism. If the Nellis Air Force Range is used for MX missile defense systems, the past and present evidence for seismicity and tectonic rupture should be evaluated carefully.

The second important aspect of tectonic activity, the rate of tectonic activity within a given mountain range, is an important factor in determining the size and rate of production of sediment from fluvial systems that originate within the mountain range and deposit their sedimentary load within the adjacent basin. Consider two different tectonic settings. The first is tectonically active and rapid uplift at the mountain front has resulted in rugged mountains with steep V-shape canyons that plunge down to the stream courses that transport sediment. In such a setting, coarse-grained sediments are produced in abundance and are delivered directly from the hillslopes into the stream subsystem where they are immediately available for transport to the basin. In a second setting of tectonic quiescence, the hillslopes are steep, but embayed mountain fronts and broad valley floors are typical. In this setting, gravel that is brought down from the hillsides to those reaches of the streams that have a U-shaped cross-valley profile is not generally delivered directly to the basin. Instead, it will remain on the flat valley floor and only the gradual weathering of these boulders reduces the particle size to that which can be transported from the mountain subsystem to the depositional basin. Within a region that has been tectonically active in the past, and generally inactive during the Quaternary, such as the Luke Air Force Range, one should expect to find fine-grained basin fills overlying coarser-grained basin fills

that were deposited at a time when the mountain fronts were tectonically active.

2.2.3.3. Local Base Level Processes

A process that changes the altitude of a point on a streambed is a local, base-level process. Base-level processes include stream-channel downcutting in the mountains (w) and erosion (e) or deposition (s) on the piedmont. These three processes are interdependent and are affected by the relative uplift (u) of the mountain front. These four base-level processes, since they affect the activity and form of the stream, the hillslope development, and the location of deposition and erosion, are responsible for the topography of the basins. (See Appendix J for an expanded discussion.)

The effects of continued and rapid uplift of mountains relative to the adjacent basins, either by continuous or pulsatory uplift, result in a distinctive suite of landforms. Figure 2:4 depicts the accumulation of thick alluvial-fan deposits adjacent to a faulted mountain front. Channel downcutting in the mountains will tend to cause the stream-channel to become entrenched into the fan apex, which will cause the locus of deposition to be shifted downslope on the fan. Uplift of the mountains relative to the piedmont counteracts the tendency to entrench the stream-channel into the fanhead. Continued channel downcutting in the mountains without trenching the fanhead can occur when the rate of uplift equals or exceeds the sum of the two local base-level processes that are tending to cause the fanhead trenching as shown by Equation 1:

$$\Delta u/\Delta t \geq \Delta w/\Delta t + \Delta s/\Delta t \qquad (1)$$

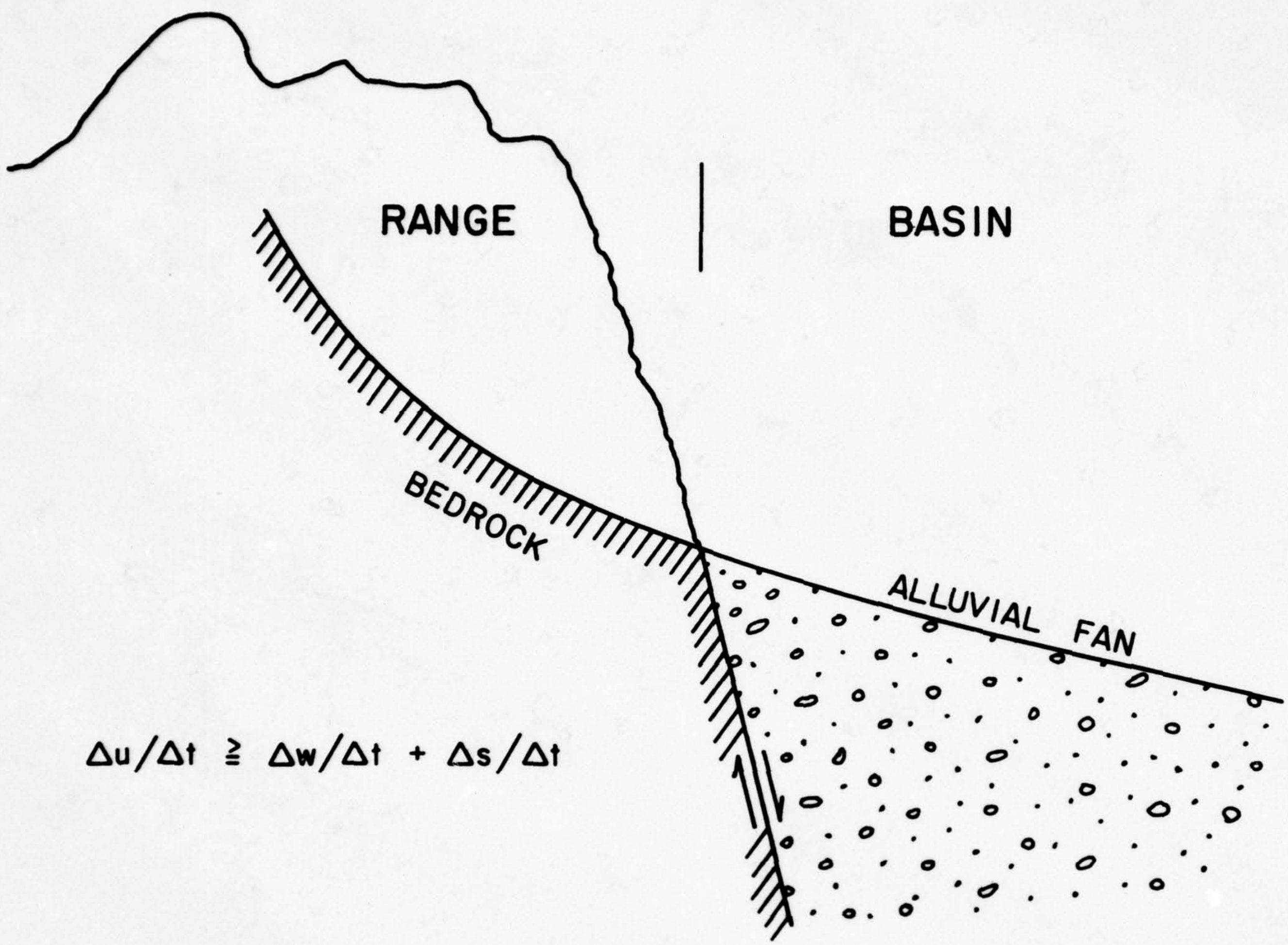

Figure 2:4 Interrelations of local base-level processes conducive for the accumulation of thick alluvial-fan deposits next to a mountain front (Bull, 1973).

Equation 1 is only one of five equations interrelating local base processes for the three different tectonic environments. The five equations shown in Table 2:1 form the basis of the three classes of relative tectonic activity of mountain fronts within a given study area during the Quaternary.

The assignment of a tectonic activity class for a given mountain front is based on parameters that describe diagnostic landform morphologies within both the erosional and depositional subsystems. The landforms described in Table 2:1 are only a few of the many diagnostic landforms for a given class. For example, class 1 landscapes, when compared with class 3 landscapes of similar total relief, climate, and rock type, have more convex ridge crests, steeper footslopes, narrower and steeper canyons, less sinuous mountain fronts, thicker basin deposits next to the mountains, better preserved spur facets, and minimal soil-profile development on the piedmont (Bull, 1973). Thus, the tectonic geomorphology model defines the interrelations of tectonic base-level change to other base-level processes by the equations of Table 2:1 and allows the assignment of an appropriate tectonic activity class by descriptions of selected landscape elements. Class 1 fronts occur in highly active tectonic areas that are generally characterized by active folding and/or faulting during the Holocene as well as the Pleistocene. Class 2 mountain fronts show evidence of activity during the Pleistocene, but not the Holocene. Class 3 mountain fronts are tectonic in origin, but were inactive throughout the Quaternary (Bull, 1977).

2.2.3.4 Geomorphic Parameters for Tectonic Activity

For the purposes of this study, six parameters were used that are reliable and fairly easy to evaluate:

TABLE 2:1 TECTONIC GEOMORPHIC PROCESSES

TECTONIC CLASS	LOCAL BASE LEVEL PROCESSES u - uplift w - channel downcutting s - piedmont deposition e - piedmont erosion t - time	LANDFORMS PIEDMONT	MOUNTAIN
1	$\Delta u/\Delta t \geqq \Delta w/\Delta t + \Delta s/\Delta t$	unentrenched alluvial fan, or fan with only Holocene deposits on fanhead	V-shape cross-valley profile in bedrock
2A	$\Delta u/\Delta t < \Delta w/\Delta t > \Delta e/\Delta t$	entrenched alluvial fan with Pleistocene surfaces on fanhead	cross-valley profile V or U-shape
2B	same as above	same as above	U-shaped cross-valley profile and embayed mountain front
3A	$\Delta u/\Delta t \ll \Delta w/\Delta t > \Delta e/\Delta t$	permanently dissected pediment	embayed mountain front
3B	$\Delta u/\Delta t \ll \Delta w/\Delta t = \Delta e/\Delta t$	undissected pediment	embayed mountain front
3C	$\Delta u/\Delta t \ll \Delta w/\Delta t < \Delta e/\Delta t$	erosional base-level fall due to contrasting piedmont and mountain lithologies. may have characterstics of tectonically active mountain front.	

Class 1 - Generally active during Holocene
Class 2 - Generally active during Pleistocene, but not Holocene
Class 3 - Inactive throughout Quaternary

(Bull, 1973)

40

1) Alluvial fans: degree of slope

2) fan-head trenching

3) age of the fan surfaces

4) Sinuosity of the mountain-piedmont junction

5) Valley cross-section

6) Preservation of spur facets.

A knowledge of the Quaternary geology of the study area is necessary in order to accurately assess the parameters, especially the distribution of alluvial surfaces of different ages. Active deposition of thick alluvial fans next to mountain fronts is indicative of class 1 tectonic conditions. The age of the oldest geomorphic surface next to the mountain front is a good indicator of the length of time that has passed since class 1 tectonic conditions last prevailed (Bull, 1977).

The Holocene surfaces (Q3) preserve the bars and swales of the original stream channels and have desert pavements with varying stages of development. The bars and swales give the Q3 surfaces a plumose pattern on aerial photography.

The late and middle Pleistocene surfaces (Q2) have lost all trace of bars and swales and have smooth desert pavements. On aerial photography these surfaces have a smooth, even-toned appearance. Q2 surfaces are very light-toned, almost white, when formed of alluvium derived from granitic rocks. When formed from metamorphic-derived alluvium, they are dark-toned. Q2 surfaces of volcanic-derived alluvium are very dark, almost black, due to the heavy coating of desert varnish on the rocks comprising the pavement. An exception to this is found in the older Q2 surfaces where the upper

soil horizons have been removed by erosion. The pavement surface is formed on the Cca horizon and is a mixture of black-coated cobbles and caliche. On aerial photography, this surface has a medium-toned, stippled appearance which is contrasted with the plumose patterning of the Q3 surfaces.

The early Pleistocene to Pliocene Q1 deposits have lost all traces of their original upper surfaces and all the soil horizons, down to the petrocalcic horizon, due to the long period of erosion to which they have been subjected. Their present topography is low, parallel ridges with even crests separated by parallel ravines with even slopes. Q1 deposits are exposed only on piedmonts where the predominant fluvial activity has been erosive. Otherwise, these Q1 deposits would have been buried by younger alluvium. Since deposition on the piedmont is one result of tectonic activity, the presence of Q1 exposed along a mountain front is a clear indication of a lack of tectonic activity, at least during most of the Quaternary. See Chapter 5 for detailed descriptions of Quaternary alluvium of different ages and their geomorphic surfaces.

Alluvial fan morphology is also a useful indicator of tectonic activity. A bajada of steep (10^{o}) alluvial fans accumulating a thick (100 m) deposit of sediments onto a gentle piedmont slope is one clear indication of a tectonically active mountain front. Thin, gently sloping (1^{o} to 2^{o}) alluvial fans that are only slightly higher than the adjacent areas of piedmont are most likely the result of climatic perturbations. However, between these two extremes there exist many alluvial fans that could have been caused by either, or both, of these changes to the fluvial system. Fan-head trenching indicates that a period of time has passed since the event, whether it be tectonic or climatic, which resulted in deposition on the head of the fan. An alluvial fan whose fanhead is entrenched and displays Q3 surfaces next

to the mountain front indicates that fan formation activity ceased during the Holocene. This would suggest a class 1 mountain front, if indeed the fan was caused by a tectonic event. An entrenched, Pleistocene-surfaced fan indicates activity during the Pleistocene, or a possible class 2 mountain front. In order to ascertain the cause of the fans, the rest of the mountain front and stream channel morphologies must be examined.

The sinuosity of the mountain front is the next parameter to be examined. Tectonic activity will tend to keep the front coincident with the tectonic structure so that the junction between the mountains and the piedmont is a fairly straight or gently curving line. Opposing this is the tendency for streams to erode irregularities into the mountains. Thus, with the passage of time from the last tectonic event, the mountain front will become increasingly irregular. The mountains will retreat from the frontal structure forming pediments and the canyons will become embayed. The degree of erosional modification of tectonic structures can be measured by a mountain-front sinuosity index. Mountain-front sinuosity (S) is the ratio of the length along the edge of the mountain-piedmont junction (Lmf) to the overall length of the mountain front (Ls) as shown in Equation 2:

$$S = \frac{Lmf}{Ls} \tag{2}$$

(Bull, 1977)

Values of S are, in part, a function of the scale and detail of the maps or aerial photographs. Values will be higher for larger scale maps and photos as opposed to smaller scale, but in either case the proportions between individual mountain fronts will remain approximately the same.

Studies made elsewhere in the Sonoran and Mojave deserts show that each of the tectonic activity classes of Table 2:1 has fairly distinctive ranges of

mountain-front sinuosity. Class 1 fronts generally range from 1.0 to 1.6, class 2 from 1.4 to 3, and class 3 from 2 to more than 7 (Bull, 1977). For the purposes of this study no attempt was made to obtain numerical values for the sinuosity index, rather the sinuosity was visually estimated for each mountain front and a category assigned based on the amount of sinuosity. Low sinuosity is the category for S values from 1 to 2. Moderate sinuosity, S values in the 2 to 3 range. High sinuosity, S values greater than 3.

Next to be considered is the mountain valley morphology, particulary the valley or canyon cross-section adjacent to the mountain front. Continued mountain uplift will insure that the streams will continue to erode their valleys downward, thus maintaining V-shaped canyons. After the cessation of tectonic activity, the stream will gradually lose its ability to erode downward, and will erode laterally as the hillslopes retreat, resulting in a flat-floored or U-shaped valley. Eventually, the valley will become an embayment of the piedmont. In class 1 landscapes, the canyons are distinctly V-shaped with the channel of the stream being essentially the same width as the floor of the canyon. In class 2 terrains, the stream channel is significantly narrower than the floor of the canyon. The canyon is still a separate entity from the piedmont and has a noticeably steeper gradient. A class 3 valley is simply an extension of the pediment.

The last parameter is the degree of preservation of faceted spurs. In tectonically active areas, the ridge spurs will appear truncated along the tectonic structure forming triangular spur facets. These spur facets will be subjected to erosional degradation once the tectonic activity has ceased. In class 1 landscapes, the faceted spurs will be well-preserved and easily discernable, since their faces will not have been subjected to

the ravages of erosion. In class 2 landscapes, the faceted spurs will be deeply gullied and dissected by streams. By the time class 3 conditions have been reached, the faceted spurs will have been obliterated. The contrast in preservation of faceted spurs in class 1 and 3 landscapes is shown in Appendix I.

An exception to the normal tectonic geomorphic scheme that has been outlined here is the situation that can sometimes occur when there has been a drastic increase in the rate of erosion on the piedmont side of the mountain-bounding fault. If the fault is also a lithologic boundary, with the rock type on the piedmont side of the fault being considerably more easily eroded than the rock on the mountain side, there could be an erosional base-level fall with the fault as its mountain-side boundary. This would result in seemingly class 1 landforms such as active alluvial fans, V-shaped valleys, and even faceted spurs, all of them lined up quite nicely along an inactive fault. An indicator of this situation would be a short mountain-front segment showing class 1 characteristics along a mountain front that is otherwise class 3. While the boundary between the contrasting lithologies does not necessarily have to be a fault, a non-fault contact would probably not have the distinct linearity of a fault. Close scrutiny of the total geologic and geomorphic situation is required in order to correctly analyze such a mountain-front base-level fall of strictly erosional, non-tectonic origins. This type of mountain front is class 3C on Table 2:1. While this type of front is tectonically inactive, it still represents a base-level fall and, thus, affects sediment distribution in much the same manner as a tectonically active front.

Strike-slip faulting presents a much different problem in tectonic analysis than does faulting of a primarily vertical nature. Strike-slip faulting that has only a small vertical component to change the base level of fluvial systems will not display the typical landforms of a tectonically active mountain front. Instead, strike-slip faulting will result in landscape features such as disrupted drainage patterns and offset ridgelines. Identification of strike-slip faulting is included in this report to give a more complete picture of the Quaternary tectonism of the study area and because some of the faults that were active during the late Cenozoic within the Luke Air Force Range probably had a strike-slip component.

2.2.3.5 Method of Analysis

A thorough search of the entire study area was made using the largest scale (1:24,000 and 1:62,500) topographic maps available. Mountain fronts with low to moderate sinuosity and marked linearities within the mountain areas were annotated on both the large scale maps and also on a 1:250,000 scale map of the entire study area. The available aerial photography coverage was then plotted on the 1:250,000 scale map to facilitate the determination of which photos could be used to study a given area. Figure 2:5 shows the photographic coverage. Using the aerial photographs, the mountain fronts were qualitatively described and evaluated for the geomorphic parameters that would indicate their tectonic activity class. Receiving particular scrutiny were those fronts that the topographic map search showed to have low to moderate sinuosity and other landforms suggestive of tectonic activity. Also analyzed was the interior of the mountainous areas to determine if there was any evidence of active tectonism or rejuvenation of old faults. The basin and piedmont areas were scanned for any disruption of drainage patterns or scarps that might indicate tectonic activity. To fill in the

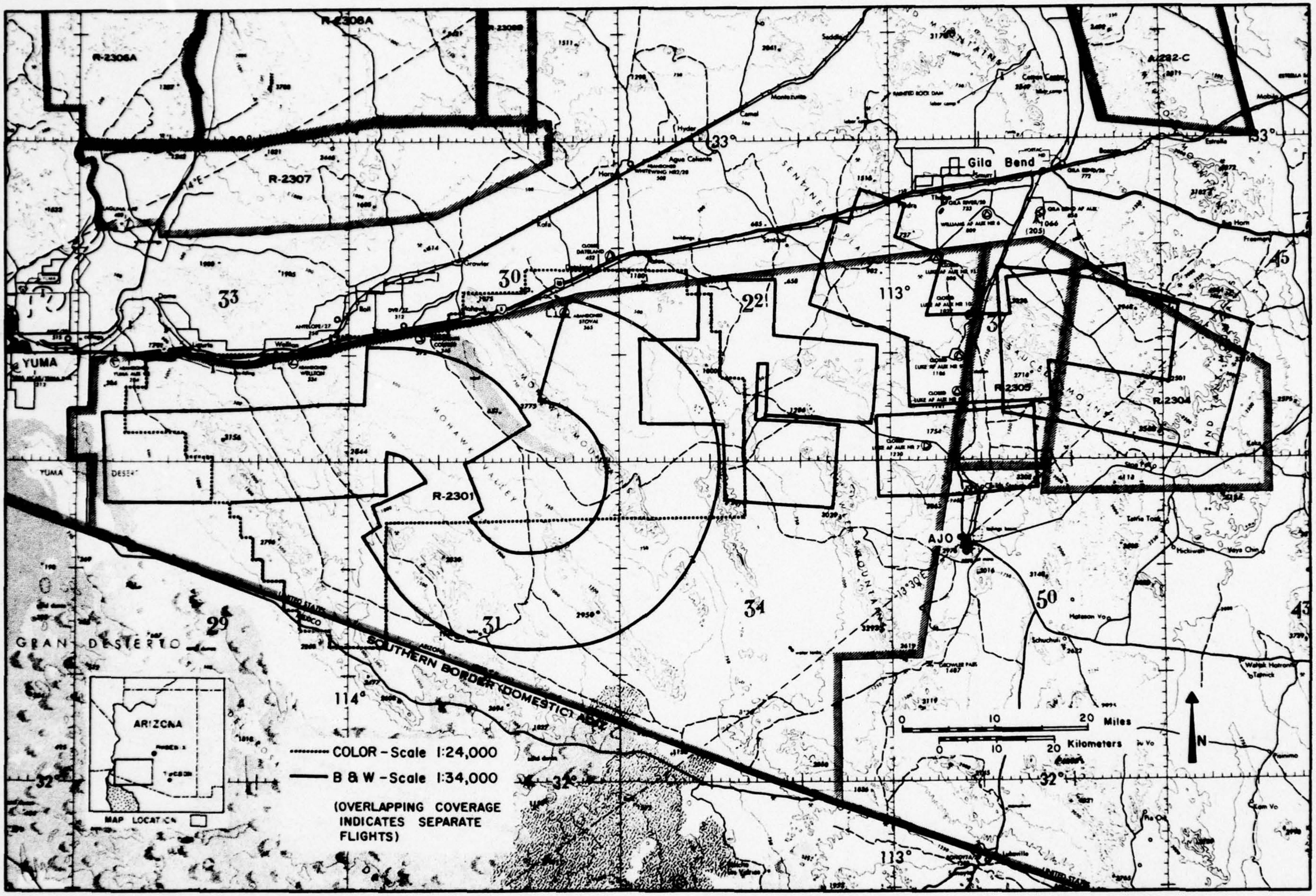

Figure 2:5 Aerial photography coverage of the Luke Air Force Range.

gaps in the airphoto coverage and to obtain a closer and more complete look at selected areas, an aerial reconnaissance and photographic mission was made of the entire study area on 3 December 1978.

2.2.3.6 Tectonic Geomorphology of the Luke Air Force Range

In this section, each mountain range and its mountain fronts are described in detail and evidence presented for the assignment of the individual mountain front segments to a tectonic activity class. Figure 2:6 shows the location of the mountain front segments studied and their tectonic activity classes. Table 2:2 gives a summary of the tectonic geomorphology. Mountain fronts that are not assigned a tectonic activity class are judged to be either non-tectonic in origin or lacking in any signs which would indicate tectonic origins.

2.2.3.6.1 Gila Mountains

The Gila Mountains are located close to the Gila and Colorado Rivers, which both show a history of downward erosion of their valleys (Hunt, 1969). The streams that drain the Gila Mountains empty into the Gila River which has caused a continual lowering in the base level of these streams. By lowering the base level, the streams have eroded deep channels through a sequence of alluvium that covers the entire Quaternary and perhaps into the latest Tertiary as well (see Fig. 5:1). The exposure of this broad range of alluvial material with the oldest abutting directly against the mountain front indicates that the fluvial systems of the Gila Mountains have throughout the Quaternary experienced pulses of headward erosion along their entire reaches from the Gila River to the ridge crests of the mountains. There is no sign of any tectonic activity that would have caused the deposition of fresh alluvium along the mountain fronts and buried the older deposits. Front E2, also

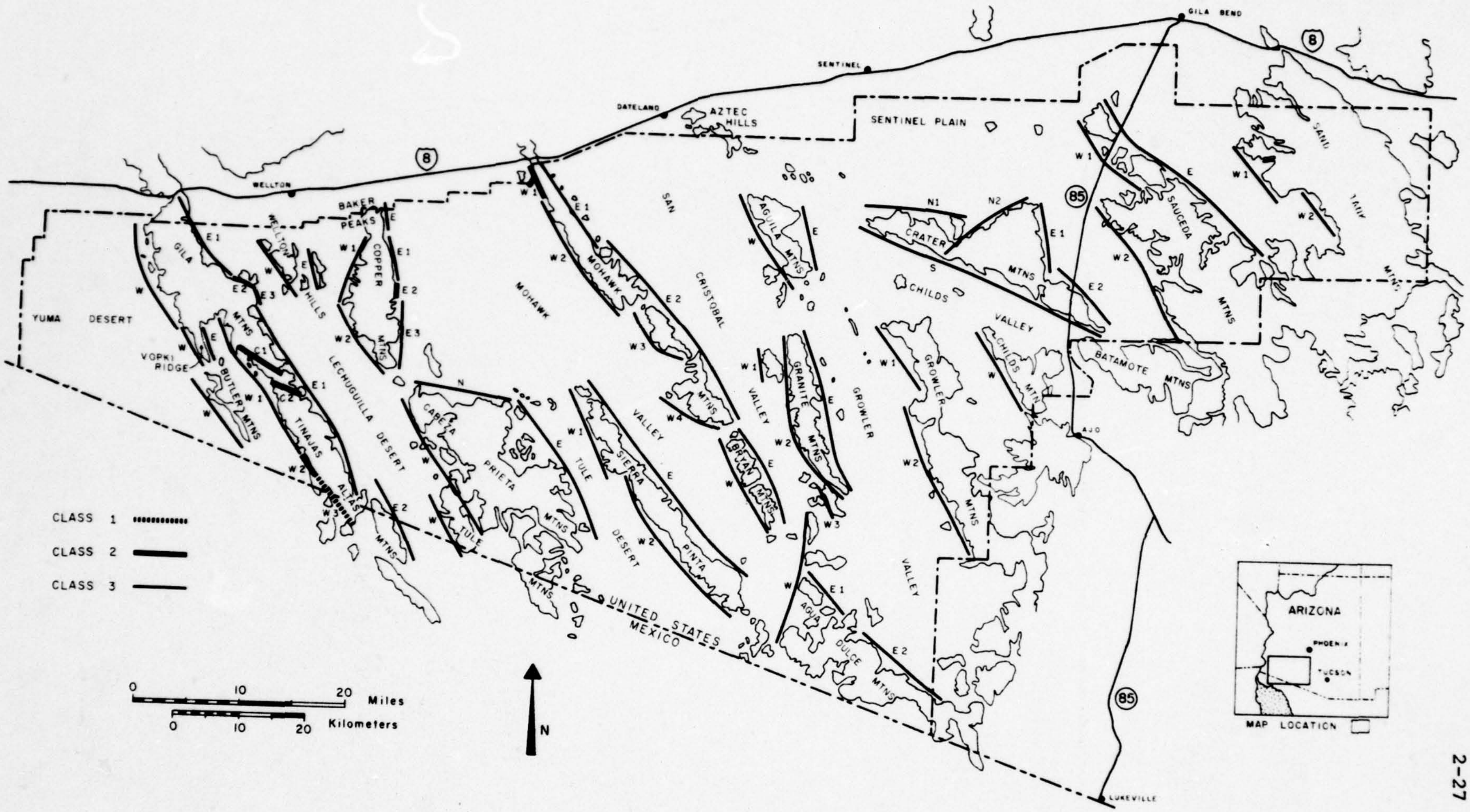

Figure 2:6 Tectonic activity of the Luke Air Force Range, Arizona.

TABLE 2:2a TECTONIC GEOMORPHIC SUMMARY OF THE LUKE AIR FORCE RANGE

MOUNTAIN FRONT SEGMENT[1]		ALLUVIAL LANDFORMS[2]	FANHEAD SURFACE	MTN-FRONT SINUOSITY[3]	VALLEY X-SECTION	TRIANGULAR FACETS	TECTONIC CLASS	REMARKS
Gila Mtns -	W	disct fans pediment	Q1	high	U-shape	none	3B	
	E1	disct fans terraces	Q1	high	U-shape	none	3B	
	E2	small high angle fans	Q3	low	V-shape	dissected	3C	contrasting lithology accelerated piedmont erosion
	E3	disct fans pediment	Q2	high	U-shape	none	3B	
Vopki Ridge -	W	disct fans	Q2	high	U-shape	none	3B	
	E	backfilled valleys	none	high	U-shape	none	3B	east side of ridge buried by alluvium from Gila Mtns
Butler Mtns -	W	streams flow across range	none	high	U-shape	none	3B	range is buried by alluvium from Gila/ Tinajas Altas Mtns
Gila/Tinajas - Altas Mtns	W1	low angle entrenched fans	Q2	moderate to high	U-shape	dissected to none	3B	
	E1	low angle entrenched fans	Q2	high	U-shape	none	3B	
	C1	med angle entrenched fans, disrupted drainage, backfilled valley	Q2-Q3	moderate	U-shape	dissected	2B	interior fault poss strike-slip, shows disruption of drainage patterns
	C2	low angle fans, both entrenched and unentrenched	Q2-Q3	low	U-shape	undissected	2A	interior fault poss left lateral strike-slip, ridgeline off-sets same sense & amt.
Tinajas Altas - Mtns	W2	low angle entrenched fans	Q2-Q3	moderate	U-shape	dissected	2B	
	W3	high angle slightly entrenched fans	Q3	low	V-shape	dissected	1	short (5km) front segment, very low sinuosity, no con-trasting lith to account for base-level fall.
	E2	exhumed pediment	Q2	high	U-shape	none	3A	
Wellton Hills -	W	pediment embayments almost no fan acty	Q2	moderate	U-shape	none	3B and 3A	range partially buried in alluvium
Baker Peaks -	E	entrenched low angle fans, exhumed pediment	Q2	high	U-shape	none	3B	
Copper Mtns -	W1	exhumed incised pediment embayed valleys	Q2	high	U-shape	none	3A	
	W2	entrenched low angle fans	Q2	high	U-shape	none	3B	
	E1	low angle entrenched fans	Q2	moderate	U-shape	none	3B	
	E2	moderate to low angle entrenched fans	Q2	moderate	U-shape	dissected	2B/3B	signs of acty very slight
	E3	low angle entrenched fans	Q2	high	U-shape	none	3B	
Cabeza Prieta - Mtns	W		Q2	high	U-shape	none	3B	
	N		Q2	high	U-shape	none	3B	
	E		Q2	high	U-shape	none	3B	
Tule Mtns -	W	dissected pediment		high	U-shape	none	3A	

TABLE 2:2b TECTONIC GEOMORPHIC SUMMARY OF THE LUKE AIR FORCE RANGE

MOUNTAIN FRONT SEGMENT[1]		ALLUVIAL LANDFORMS[2]	FANHEAD SURFACE	MTN-FRONT SINUOSITY[3]	VALLEY X-SECTION	TRIANGULAR FACETS	TECTONIC CLASS	REMARKS
Sierra Pinta -	W1	low angle entrenched fans	Q2	high	U-shape	none	3B	
	W2	low angle entrenched fans	Q2	high	U-shape	none	3B	
	E	low angle entrenched fans	Q2	high	U-shape	none	3B	
Mohawk Mtns -	W1	high angle entrenched fans	Q3	moderate	U-shape	dissected	2B	Holocene fan accumulation and thickness of deposits suggests Pleistocene activity
	W2	moderate to low angle entrenched fans	Q2-Q3	high	U-shape	none	3B	
	W3	moderate to low angle entrenched fans	Q2-Q3	high	U-shape	none	3B	
	W4	low angle entrenched fans	Q2	high	U-shape	none	3B	
	E1	moderate to high angle entrenched and unentrenched fans	Q3	high	U-shape	none	3B	fans are thin prob resulting from climatic changes
	E2	low angle entrenched fans pediments	Q2	high	U-shape	none	3B	
Bryan Mtns -	W	low angle entrenched fans	Q2	high	U-shape	none	3B	
	E	low angle entrenched fans	Q2	high	U-shape	none	3B	
Aguila Mtns -	W	low angle fans some entrenchment	Q2-Q3	high	U-shape	none	3B	
	E	low angle entrenched fans	Q2-Q3	high	U-shape	none	3B	
Granite Mtns -	W1	low angle entrenched fans	Q2	high	U-shape	none	3B	
	W2	low angle entrenched fans	Q2	high	U-shape	none	3B	
	W3	low angle entrenched fans	Q2	high	U-shape	none	3B	
	E	low angle entrenched	Q2	high	U-shape	none	3B	
Agua Dulce Mtns -	W	pediment embayments low angle fans	Q2	high	U-shape	none	3A/3B	
	E1	low angle fans	Q2	high	U-shape	none	3B	
	E2	moderate to low angle entrenched fans	Q2	high	U-shape	none	3B	
Growler Mtns -	W1	low angle fans	Q2	high	U-shape	none	3B	
	W2	moderate to low angle entrenced fans	Q2	moderate	U-shape	none	3B	numerous slump blocks along north half of front
Childs Mtn -	W	moderate angle entrenched fans	Q2	moderate	U-shape	none	3B	fans thin
Crater Mtns -	S	moderate to low angle entrenched fans	Q2	moderate	U-shape	none	3B	
	N1	low angle fans	Q2-Q3	high	U-shape	none	3B	
	N2	low angle fans	Q2-Q3	high	U-shape	none	3B	
	E1	low angle fans	Q2-Q3	high	U-shape	none	3B	
	E2	disct pediment	none	high	U-shape	none	3A	

TABLE 2:2c TECTONIC GEOMORPHIC SUMMARY OF THE LUKE AIR FORCE RANGE

MOUNTAIN FRONT SEGMENT$_1$		ALLUVIAL LANDFORMS$_2$	FANHEAD SURFACE	MTN-FRONT SINUOSITY$_3$	VALLEY X-SECTION	TRIANGULAR FACETS	TECTONIC CLASS	REMARKS
Sauceda Mtns	- W1	low angle fans	Q2	high	U-shape	none	3B	
	W2	no fans	none	high	U-shape	none	3B	mountains well dissected
	E	fans low angle to non-existant	Q3 where present	high	U-shape	none	3B	
Sand Tank Mtns	- W1	no fans	none	high	U-shape	none	3B	
	W2	low angle fans	Q1	high	U-shape	none	3B	fans well dissected

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(1) W - West
E - East
N - North
S - South
C - Central (interior fault scarp)
Fronts numbered generally north to south

(2) Low angle fans: Surface slope 1^{o} - 2^{o}
Moderate angle fans: Surface slope 2^{o} - 5^{o}
High angle fans: Surface slope > 5^{o}

(3) Sinuosity Index (see Text, Equation 2)
Low sinuosity: S = 1 to 2
Moderate sinuosity: S = 2 to 3
High sinuosity: S > 3

known as the Sheep Mountain Fault, is often referred to as an active mountain front (Fugro, 1975). The front has low sinuosity, faceted spurs, and the alluvial fans are quite steep (Fig. 2.7 and Fig. 2:8). However, close inspection of this front shows that outcrops of bedrock stick up between and even through the fans, some 200 meter-high hills are less than 1 km onto the piedmont from the fault, and there is a profound lithologic contrast between the mountains and the piedmont. The mountains are granite and the piedmont is amphibolite which, immediately adjacent to the mountain front, is highly sheared, even mylonitic in places, and offers little resistance to erosion (Tucker, Steiner & Budden, 1974). This is a case of aggressive headward stream erosion compounded by contrasting lithologies which has resulted in an erosional scarp along an old, inactive fault having many of the geomorphic characteristics of an active mountain front.

2.2.3.6.2 Vopki Ridge

This ridge has an overall linearity that suggests tectonic origins, however, the mountain fronts themselves are quite sinuous with the valleys well-embayed with alluvial fills. Both fronts are buried in alluvium, the east front more so than the west.

2.2.3.6.3 Butler Mountains

Here is much the same situation of alluvium-buried mountains as Vopki Ridge, but carried to extremes. The range is little more than a collection of inselbergs sticking up through the alluvial cover that has been washed down from the Gila and Tinajas Altas Mountains.

2.2.3.6.4 Gila/Tinajas Altas Mountains

Fronts W1 and E1 both display the same sort of features with low-angle, entrenched, Pleistocene-surfaced fans and high front-sinuosity (Fig. 2:9) as well as a

Figure 2:7 Gila Mountains front W2. Class 3C erosional scarp.

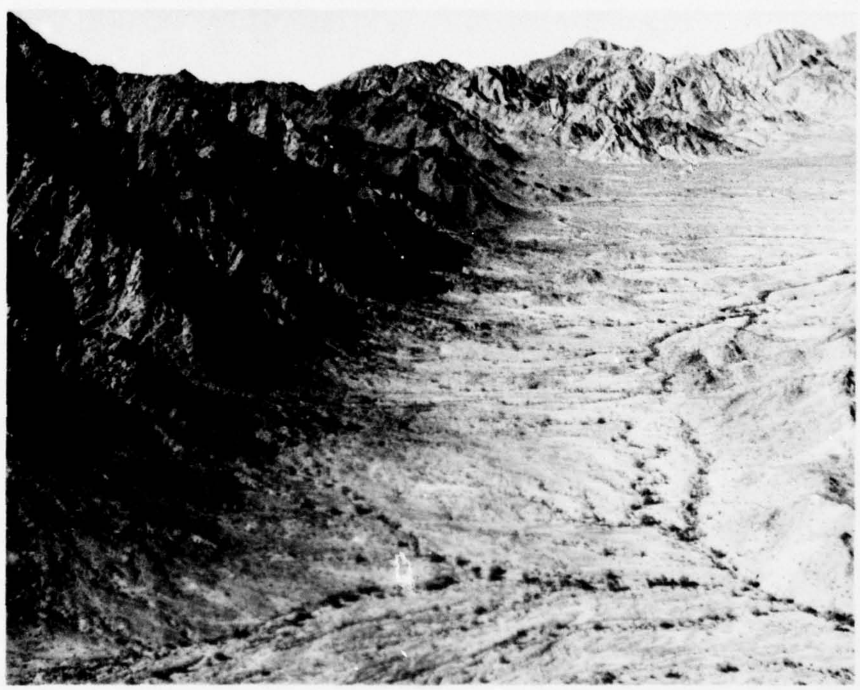

Figure 2:8 Gila Mountains front W2. View parallel to front.

Figure 2:9 Tinajas Altas Mountains, south end of front El. Typical class 3B landscape.

liberal sprinkling of pediment inselbergs across the piedmont. All of these landforms point to a lack of Quaternary tectonism for these fronts. One Holocene fan along front E1 makes its anomalous intrusion onto this scene, but this fan has been caused by a stream that changed course sometime in the late Pleistocene or early Holocene to cross a ridge spur, increased its gradient and sediment load, and deposited this alluvium onto the older piedmont surfaces. The two interior scarps of C1 and C2 show a somewhat different situation from the normal mountain fronts. Scarp C1, running mostly along the west side of the Gila Mountains and into Cipriano Pass, displays a markedly reduced amount of sinuosity when compared to the exterior fronts. It has triangular facets with only a moderate amount of stream dissection. The alluvial fans along this scarp have a very gentle slope which tends to indicate a lack of vertical movement along this fault. In the Cipriano Pass area, there are some anomalous stream patterns. Backfilling with Pleistocene and Holocene alluvium is associated with this scarp. The tectonic activity along C1 was during the Pleistocene and was probably strike-slip in nature. Scarp C2 is much the same situation as C1 except that it is marked by a line of offset ridgelines between the southwest end of Cipriano Pass and the south end of Raven Butte. All of these ridgeline offsets are of the same sense (left-lateral) and of roughly the same amount (.2 km). The facets formed by these offset ridges are largely undissected, but the intervening, Pleistocene-surfaced valleys show no disturbance or drainage pattern offset.

2.2.3.6.5 Tinajas Altas Mountains

Front W2 shows signs of increasing tectonic activity to the southeast with a progressive decrease in sinuosity and narrowing of the valleys. The fanheads show enough Q2 surfacing to indicate Pleistocene activity. At the northwest

end of W2 is a large abandoned alluvial fan with Holocene fanhead deposits (Fig. 2:10). The stream that built up this fan has been pirated and now enters the piedmont further to the northwest. This unusual feature may owe its origin to the apparent Pleistocene activity along the adjacent mountain front segment. Front W3 has a sinuosity index that approaches 1 and is also marked by steep-sloped, Holocene-surfaced fans that are only slightly entrenced (Fig. 2:11 and Fig. 2:12). Prominent triangular facets complete this picture of a Holocene-active mountain front. This does not seem to be an erosional scarp like the Gila Mountains front E2. There is no contrasting lithology to indicate an erosional cause of the base-level fall. There are some 100-meter hills on the piedmont side of the fault which would make this an internal front instead of a mountain-bounding front. This is consistent with the close-spaced horst and graben structure that appears to prevail in southwest Arizona (Tucker, 1979). Front E2 at the extreme southeast end of the range is a clear case of Quaternary inactivity with terraces and exhumed pediment indicating a piedmont that has had a predominately erosional, rather than depositional history.

2.2.3.6.6 Wellton Hills

This range is only slightly more than a grouping of inselbergs and gives no indication of Quaternary tectonism. Scattered patches of dissected pediment confirm this conclusion (Fig. 2:13).

2.2.3.6.7 Baker Peaks

Only the east side of this range displays anything approaching a tectonic front. The high sinuosity, embayed valleys, and an extensive area of exhumed pediment indicates a profound lack of activity. The lithology of this range

Figure 2:10   Tinajas Altas Mountains fronts W1 and W2. Large abandoned alluvial fan in center of photo no longer has any major stream channels emptying onto it. Class 2B front W2 beyond. Northwest end of front W3 offset to the right beyond front W2.

Figure 2:11 Tinajas Altas Mountains front W3. Distant view.

Figure 2:12 Tinajas Altas Mountains front W3. Class 1 tectonic activity. Cabeza Prieta Mountains in distance.

Figure 2:13 Wellton Hills. Gila Mountains in distance.

Figure 2:14 Baker Peaks. Copper Mountains in background.
Tinajas Altas Mountains in distance.

is quite complex and varied. Figure 2:14 gives an overall view of the Baker Peaks and the adjoining Copper Mountains.

2.2.3.6.8 Copper Mountains

The east front is quite linear, especially in the north (Front E1), but this is largely due to the influence of a stream which closely parallels the front. Front E2 shows some slight hints of Pleistocene tectonism in the form of poorly preserved triangular facets and steeper than normal, Pleistocene-surfaced fans. This front segment has been assigned a 2B tectonic classification, but only marginally. Front E3, with its high sinuosity and deep valley embayments, shows no signs of activity. The west fronts show a similar lack of activity, especially along W1. This front is marked by a considerable area of exhumed pediment with deeply incised stream channels (Fig. 2:15). Front W2 shows extensive embayment of its valleys (Fig. 2:16).

2.2.3.6.9 Cabeza Prieta Mountains

This entire range, with its chaotic landscape and complicated lithology, is so deeply embayed and so highly sinuous that it may even be stretching things a bit to call the mountain fronts tectonic in origin (Fig. 2:17). The interior of the range is cut through with the traces of numerous northwest-trending faults and a few west-trending faults. This faulting carries through to the edges of the range and appears to given the mountain fronts, such as they are, a vague linear control along those two trends.

2.2.3.6.10 Tule Mountains

The west front of the Tule Mountains is a dissected pediment surface. The other front segment, also facing west, is almost entirely across the border in Mexico and was not considered here.

Figure 2:15 North end of Copper Mountains. Exhumed pediment adjacent to front W1 indicative of a class 3A front.

Figure 2:16 West side of Copper Mountains. Front W2 in foreground. Erosional scarp in background. Lower right quadrant of photo shows a good example of a pediment embayment.

Figure 2:17 Cabeza Prieta Mountains. Tinajas Altas Mountains, Raven Butte, and Gila Mountains in distance.

Figure 2:18 Sierra Pinta front W2. Class 3B. Granite/ Metamorphic lithologic contact in center of photo. Bryan, Granite, and Growler Mountains in distance.

2.2.3.6.11 Sierra Pinta

All fronts of the Sierra Pinta have the same sort of features which are very typical of the tectonically inactive mountain fronts across southwestern Arizona. The mountain range may be quite linear, but the mountain fronts are highly sinuous, showing the great amount of erosional retreat from the structure or structures that formed the range. The alluvial fans have very gentle gradients which continue right up to the sharply defined mountain edges (Fig. 2:18).

2.2.3.6.12 Mohawk Mountains

From a distance and on a small scale map, the Mohawk Mountains and the Sierra Pinta look very similar. However, on a closer inspection, their mountain fronts are quite different. The north part of the range, specifically front segments E1, W2, and W3, has Holocene-surfaced alluvial fans of moderate gradient (Fig. 2:19). The small size of these fans, together with the high sinuosity of these fronts, indicates that their origin is probably climatic rather than tectonic. Front W1 has the same sort of fans, but thicker. However, this front is less sinuous than the others and there are triangular facets visible. Therefore, it is a class 2B front (Fig. 2:20). Fronts E2 and W4 are heavily embayed and have numerous inselbergs on the piedmont. There are many fault traces and erosional scarps in the interior of the Mohawks, none of them show any signs of activity (Fig. 2:21).

2.2.3.6.13 Bryan Mountains

This range has inactive mountain fronts of much the same form as the Sierra Pinta (Fig. 2:22).

Figure 2:19 Mohawk Mountains front El. Class 3B. MX Test Trench in left foreground.

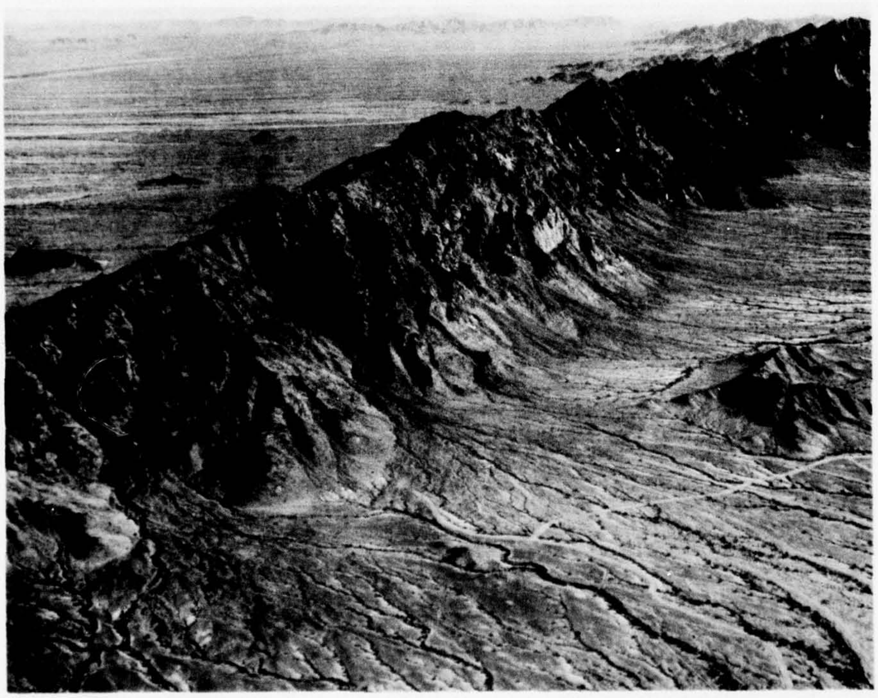

Figure 2:20 Mohawk Mountains front Wl. Class 2B tectonic activity.

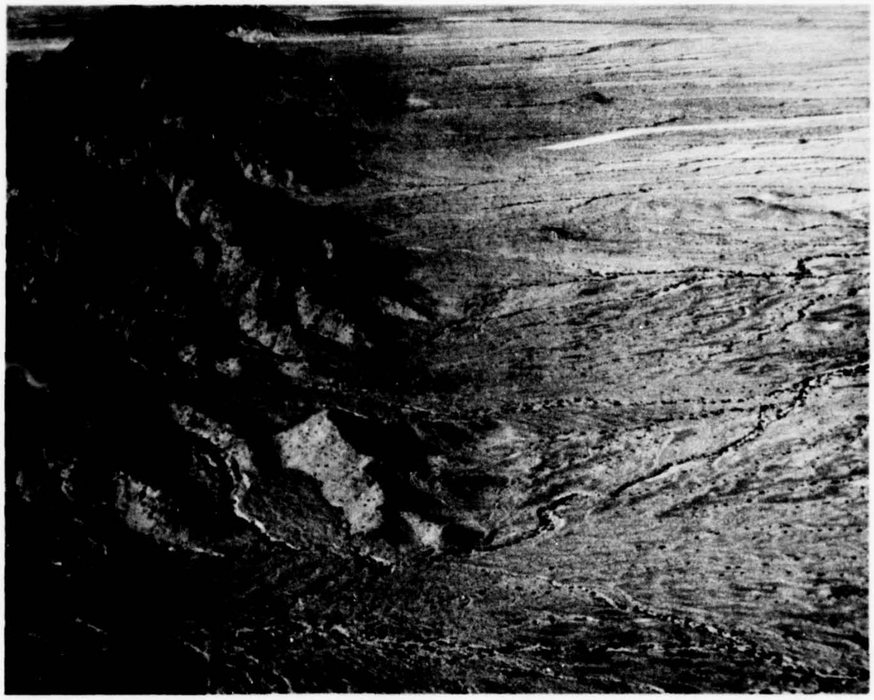

Figure 2:21 Mohawk Mountains front El. An erosional fault scarp running at a slight angle to the front can be seen in the mountains.

Figure 2:22 Bryan Mountains. Sierra Pinta in distance.

2.2.3.6.14 Aguila Mountains

This volcanic range has deeply embayed mountain fronts which display only vague hints of linearity, although the northwest-trending structural grain of the region is evident in the interior of the mountains.

2.2.3.6.15 Granite Mountains

The fronts of the Granite Mountains are virtually identical to those of the Sierra Pinta (Fig. 2:23).

2.2.3.6.16 Agua Dulce Mountains

This range of low hills lacks the sharply defined mountain/piedmont boundary of most of the ranges in southwest Arizona (Fig. 2:24). The west front is pedimented and the knobs and low hills rising to the main mountain mass along the east fronts suggest a developing pediment.

2.2.3.6.17 Growler Mountains

The west front is an obvious scarp although this appearance is exaggerated by the eastward-dipping basalt flows that cap the range (Fig. 2:25). Both west front segments are moderate to highly sinuous and the thin alluvial fans give no suggestion of tectonic activity. The north half of front W2 is much more irregular than the rest of the west front and appears to be covered with slump blocks (Fig. 2:26). The east side of the Growlers does not appear to be a tectonic front. The eastward-dipping basalt flows gradually merge with the valley of Daniels Arroyo to the east.

2.2.3.6.18 Childs Mountain

Only the southwest-facing side of Childs Mountain appears to be tectonic due to its linearity and moderate sinuosity. None of the other landform features present give any hint of Quaternary activity.

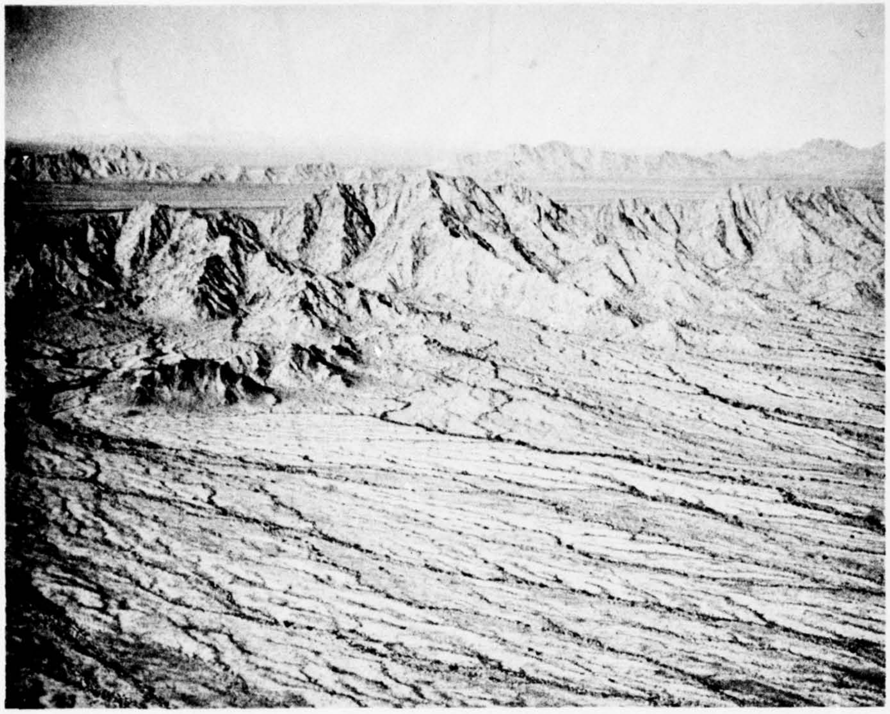

Figure 2:23 Granite Mountains front E. Class 3B.

Figure 2:24 Agua Dulce Mountains. Piedmont development approaching pedimentation.

Figure 2:25 Growler Mountains. South end of front W2.

Figure 2:26 Growler Mountains, north half of front W2. Slump blocks along the west face of the range.

Figure 2:27   Crater Mountains front S.

2.2.3.6.19 Crater Mountains

The south front is much like the west front of Childs Mountain since it is linear and has no other signs of tectonic activity (Fig. 2:27). Front N2 is the same situation. The other two fronts are so highly sinuous and so deeply embayed that even their original tectonic affinities are questionable.

2.2.3.6.20 Sauceda Mountains

The high sinuosity of front W1 and the paucity of alluvial deposition activity along fronts E and W2 preclude any Quaternary tectonic activity.

2.2.3.6.21 Sand Tank Mountains

Front W1 shows the same lack of features as E and W2 in the Sauceda Mountains. Front W2 has collected a considerable array of alluvial deposits, but they have been steadily eroded resulting in old, low-angle alluvial fans that have been well-dissected. There is also a suggestion of exhumed pediments near the southeast end of the front. Any tectonic activity that occurred along front W2 did so before the Quaternary.

2.2.3.7 Conclusions

The area of the Luke Air Force Range in southwest Arizona is almost entirely free of tectonic activity today. The shape of the mountains and basins is the result of a continuous process of erosion and deposition since the cessation of major basin and range tectonism in the late Miocene. What tectonic activity continued into or was initiated during the Quaternary occurred mostly in the Pleistocene with only one possible local occurrence in the Holocene. There is no evidence, other than some scattered magnitude 4 earthquakes, that any tectonism has occurred in recent times.

The magnitude of the Quaternary tectonism has, in all cases, been slight. None of the alluvial fans spawned by these pulses of uplift amounts to anything more than small deposits of coarse clastics that encroach no more than a few hundred meters onto the piedmont. Observations of streams in southwest Arizona and the sediments that they transport show that the coarse clastics picked up in the mountains are deposited on the medium angle (5^{o} to 10^{o}) alluvial fans such as those found along front E2 of the Gila Mountains (Schenker, 1977) and other areas. With the small drainage basin areas that exist in the worn-down mountains of southwest Arizona, the streams do not have sufficient power to transport anything coarser than small (10 cm) cobbles on the gentle gradient (1^{o}) of the piedmont slopes.

Along any given mountain range, all other variables being the same, the front segment with the greatest level of tectonic activity will have the greatest rate of piedmont sediment accumulation. The amount of an entrenched alluvial fan that is buried by fine piedmont sediments can be roughly approximated by extrapolating the fan surface below the alluvial cover. For a small fan extending only a couple hundred meters from a mountain front and which was produced by minor pulses of tectonic activity on the order of a few tens of meters spread over most of the Pleistocene, as is apparently the case in the study area, the buried extent of the fan is probably less than 50% greater than its above-surface area. This approximation is based on piedmont sedimentation rates discussed elsewhere in this report and subsurface examinations of piedmont alluvium (Fugro, 1976).

With the small amount and magnitude of Quaternary tectonism within the Luke Air Force Range and the very small areal extent of the resulting fluvial

deposits, it can be concluded that tectonic activity has had no appreciable effect on the distribution of sediments within this area during the Quaternary. However, the deep gravel deposits in the basin areas (Fugro, 1976) does indicate active tectonism in the late Tertiary.

At least for the Luke Air Force Range area, tectonic activity can be discounted as an independent variable affecting the model for prediction of gravel distribution. The variables of gradient, drainage basin area and relief, mountain lithology, etc., have a far greater, even overwhelming, effect on the outcome of the fluvial model.

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2.3 GEOMORPHIC ZONATION by Ran Gerson

Typical Basin and Range terrains may be ideally subdivided into several geomorphic zones (Figure 2:28):

I Mountain Range, composed mainly of exposed and some talus mantled bedrock. This zone, being actively eroded by stream systems, is composed of divides, hillslopes, channels and alluvial terraces. Lithology, structure, morphometry and climate determine the amount and quality of derived sediments.

II Pediment-Inselberg Zone, from the present mountain front to the limits of exposed or shallowly buried pediments or inselberg remnants (Figure 2:29). This area contains several components; alluvial fans of various ages or their upper portions, thinly veneered, buried bedrock pediments, and frequently inselbergs. The outer, or down-piedmont boundaries of this zone are difficult to delineate, due to burial of bedrock.

III Depositional Piedmont Zone, or Depositional Basin, built of thick deposits of alluvium, primary and secondary eolian sediments and occasionally playa clastics and precipitates. Different horizons of deposition may interfinger in space.

While Zone II may be primarily a transfer area to most fluvial sediments, Zone III is essentially a major zone of deposition. Fluvial systems cross these zones; they netly erode Zone I, partially deposit in Zone II and solely deposit in Zone III. In Zone II and especially in Zone III, external geomorphic processes intervene to alter or modify the fluvial sediment. These are mainly eolian, pedogenic and groundwater processes, which add fines and salts to the fluvial deposits.

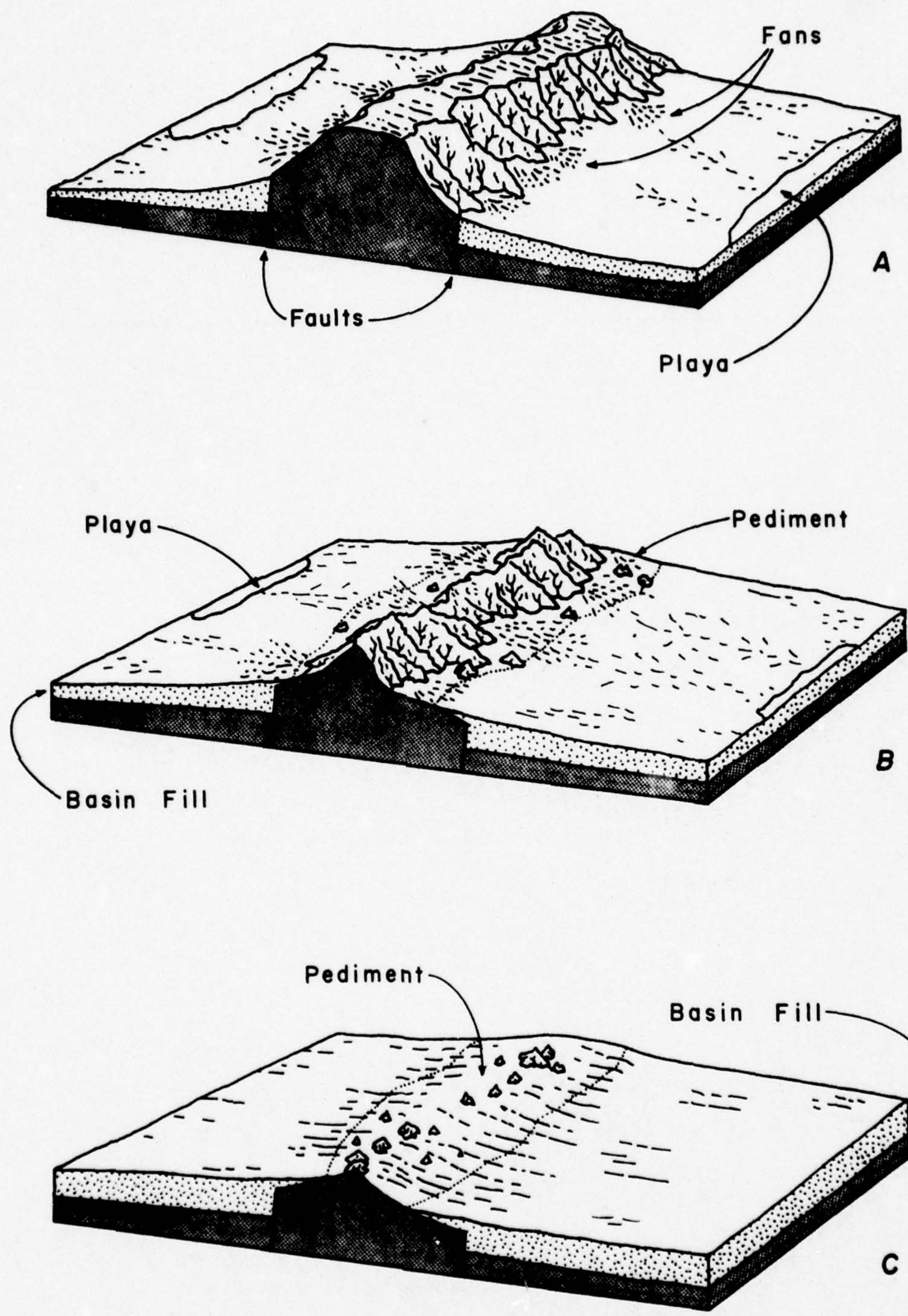

Figure 2:28 Three stages in the sculptural evolution of a mountain range (from Flint and Skinner, 1974).

Figure 2:29 Inselberg-pediment zone, eastern flank of Mohawk Mountains, southwestern Arizona.

Figure 2:30 Mantled and exposed rock-cut pediments.

A. Amphibolite, Gila Mountains, southwestern Arizona.

B. Granite, Riverside Mountains, southern California.

Degree of burial of bedrock and thickness of covering debris varied from zone to zone. In Zone I, bedrock is exposed in one-half to three-quarters of the area. The rest is covered by relatively thin colluvium, 0 to 3 mm thick.

In Zone II, bedrock is exposed mainly in inselbergs and some riverbanks in eroded pediments. It is very rare to find exposed pediments, as is the case in the Riverside Mountains, southern California (Figure 2:30), or the Santa Katherina area in southern Sinai. Thickness of alluvium generally increases from mountain fronts and inselberg slopes toward the depositional basin or main streams. A few data may help estimate the thickness of alluvium on pediments:

1. Surface slope, measured directly from topographic maps, preferably of 1:24,000 scale.
2. Pediment length measured directly from the base of mountain or inselberg fronts.
3. Pediment slope, which ranges between 30' and 7°, but averages 2° 30' (Cooke and Warren, 1973).

Assuming that the pediment is not severely eroded, one may estimate its average position by a simple equation:

$$T - L\tan 2.5^{\circ} - L^{2}\tan\alpha$$

Where T = thickness of alluvial cover at a distance L from the mountain front; 2.5° = average pediment slope, but other figures may be used, α = slope of the surface.

Several attempts to calculate pediment depth in the Mohawk Mountains, southwest Arizona, coincided, in order of magnitude, with drillhole data. Accurate data pertaining to thickness of alluvial cover of rock cut pediment may be obtained only by geophysical methods or by drilling.

Zone III is the zone of thick alluvial, eolian or playa deposition. In most cases, the thickness of clastic sediments exceeds several dozens of meters. Only in areas of step-faulted terrains may the bedrock be closer to the surface and show no evidence by imagery or topographic maps.

The boundaries between Zones II and III are obscured by alluvial burial of the bedrock. Data for coarse estimate are:

1. Location of inselbergs or mountain front.
2. Age of depositional basin faulting.
3. Assumption rates of average hillslope retreat of 10^{-4}-10^{-2} mm/yr (Young, 1972; Yair and Gerson, 1974; Mabbutt, 1977).

Buried pediments, which started to form at the beginning of the Quaternary, would be found from 0.02 to 0.0002 km from exposed mountain or inselberg fronts.

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3.0 FLUVIAL SYSTEMS IN ARID REGIONS by Ran Gerson

3.1 VARIABLES IN THE FLUVIAL SYSTEM

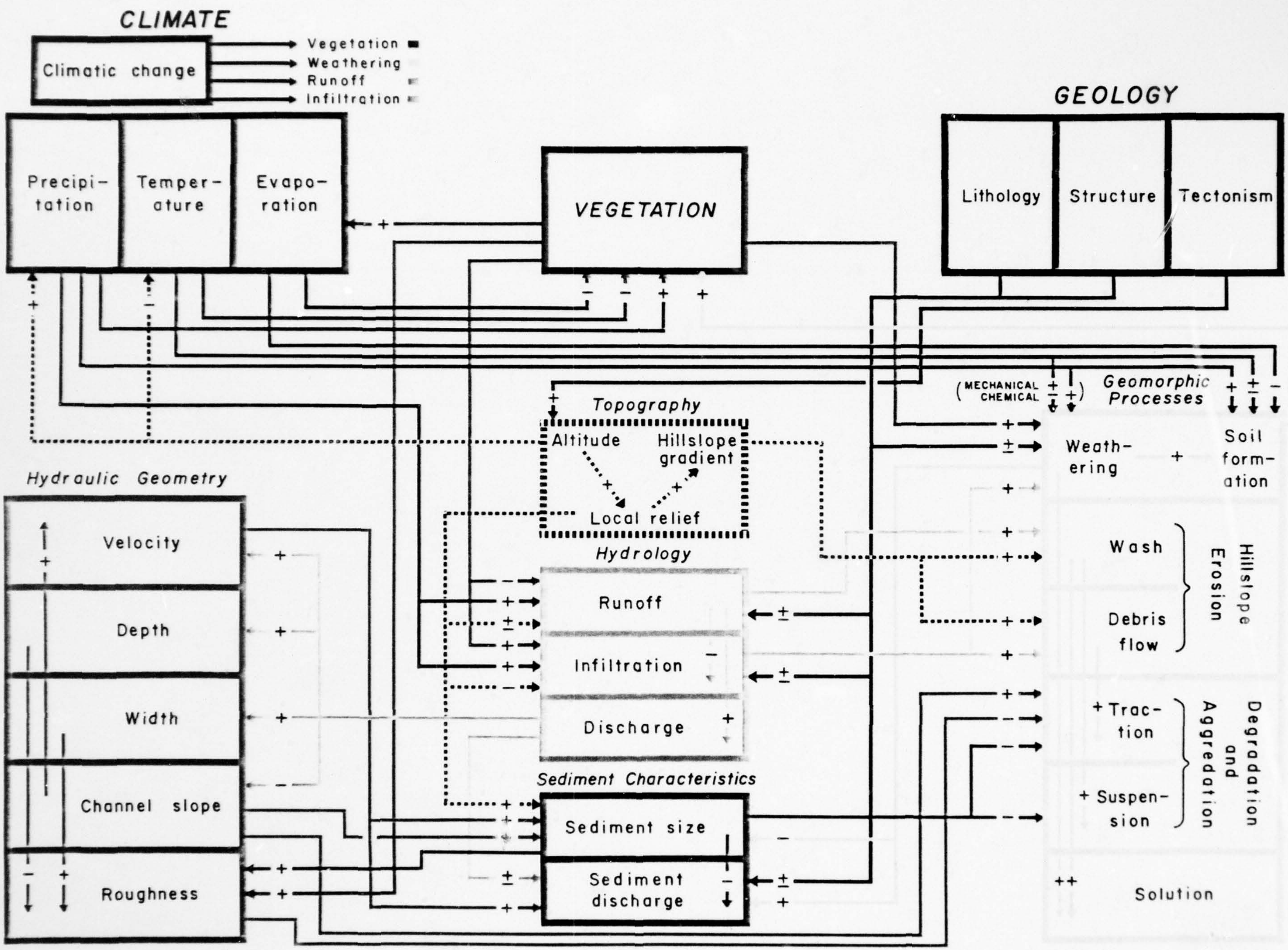
A watershed is a dynamic, open system. Its components or variables change in time and space. These variables may be grouped in the arid environment into several categories:

1. Climate. Precipitation, temperature, evaporation.
2. Geology. Lithology, structure, tectonic activity.
3. Vegetation.
4. Topography. Altitude, local relief, hillslope gradient.
5. Hydrology. Runoff, infiltration, discharge.
6. Geomorphic processes. Weathering, hillslope erosion, degradation, aggradation, solution.
7. Hydraulic geometry. Velocity, depth, width, slope, roughness.
8. Sediment characteristics. Sediment size, sediment discharge.

There is a constant feedback between many of the variables, especially within and between categories 3, 5, 6, 7 and 8, which are highly dependent on categories 1, 2 and 4 (Figure 3:1).

A general trend is, the more humid the climate, the more significant are multivariate correlations between sediment yield and landscape features, and the more effective is the use of universal equations. The main reason for this situation is the effectiveness of "homogenizing" weathering (chemical) and soil formation-vegetation factors. Also, there is a general repetition of hydrologic events in space with time, and obliteration of traces of extreme events, both on hillslopes and in stream channels (Wolman and Gerson, 1978).

Figure 3:1 Variables and interrelationships in the fluvial system (+ direct relationship; - inverse relationship).



CLIMATE
Climatic change
Vegetation
Weathering
Runoff
Infiltration
Precipi-tation
Temper-ature
Evapo-ration
VEGETATION
GEOLOGY
Lithology
Structure
Tectonism
(MECHANICAL CHEMICAL)
Geomorphic Processes
Weath-ering
Soil form-ation
Wash
Debris flow
Hillslope Erosion
Trac-tion
Suspen-sion
Degradation and Aggradation
Solution
Topography
Altitude
Hillslope gradient
Local relief
Hydrology
Runoff
Infiltration
Discharge
Sediment Characteristics
Sediment size
Sediment discharge
Hydraulic Geometry
Velocity
Depth
Width
Channel slope
Roughness

The inverse is characteristic of the arid regions:

1. Rock is exposed both in bedrock outcrops and in debris mantle. Rock composition, texture and structure highly affects weathering, infiltration, erodibility and, hence, sediment quality and yield.
2. The effects and localization of extreme events may have a very long term effect on certain facets of landscape that may not recover within the time span of occurrence of a given climatic regime.
3. The effect of climatic change is large. "Slight" changes in precipitation and temperature characteristics may well exceed the thresholds for various processes.

3.2 FLOODS IN ARID REGIONS

3.2.1 THE NATURE OF FLOODS

This section presents some of the salient features of arid fluvial systems relevant to the origin, transport and deposition of gravel.

A main feature of arid fluvial systems is their ephemeral nature, sporadic in flow and sediment transport. Flow events are short, usually ranging between a few minutes and a few dozens of minutes. They occur between one and five days a year.

The frequency of events of any given magnitude is still unknown. Absence of flow data or observation is still a major obstacle in analyzing the hydraulics of steeply rising and falling hydrographs and related sediment transport.

A lonely case of an extensively studied arid watershed is Nahal (=stream, wash) Yael, in southern Israel (Schick, 1970, 1977; Gerson and Inbar, 1974). It is a 2.0 km long basin, draining 0.6 km^2 of arid landscape, exposing various rock types, amphibolite, schist, diorite, granite and different dikes. The climate is extremely arid with a mean annual precipitation of 32 mm. Bare and talus mantled hillslopes are about equally areally distributed. Ten years of measurements and observations, utilizing five recording gauging stations and 10 recording rain gauges, passed without any high magnitude flow event. Only low to medium magnitudes were recorded and only one was actually observed in the field.

A few results of the past 10 years should be mentioned, since they demonstrate the fluvial and sedimentary activity in arid regions:

1. Flood rise is very steep and peak flow is obtained in 1 to 20 minutes. Peak flow is relatively short, 0.5 to 10 minutes.
2. There is a rapid decrease in runoff/rainfall ratio downstream, especially in the highly infiltrating alluvial fan area (see Figure 3:2A). There is a large scale water loss in the alluvium, especially in the alluvial fans (Hadley and Schumm, 1971; Slatyer and Mabbutt, 1964; Schick, 1970). These lead to a high rate increase of suspended load concentration (Schick, 1970) and its subsequent deposition at the toes of alluvial fans and further in the depositional basin. The same general trend of flow abstractions that becomes increasingly important with increasing watershed size is well-illustrated by Osborn and Rannard (1970) (Figure 3:2B).
3. There is a difference of one order of magnitude in specific maximum water yields ($m^3/sec/km^2$), of flows having recurrence intervals of 10 years (Schick, 1977, Figure 6).

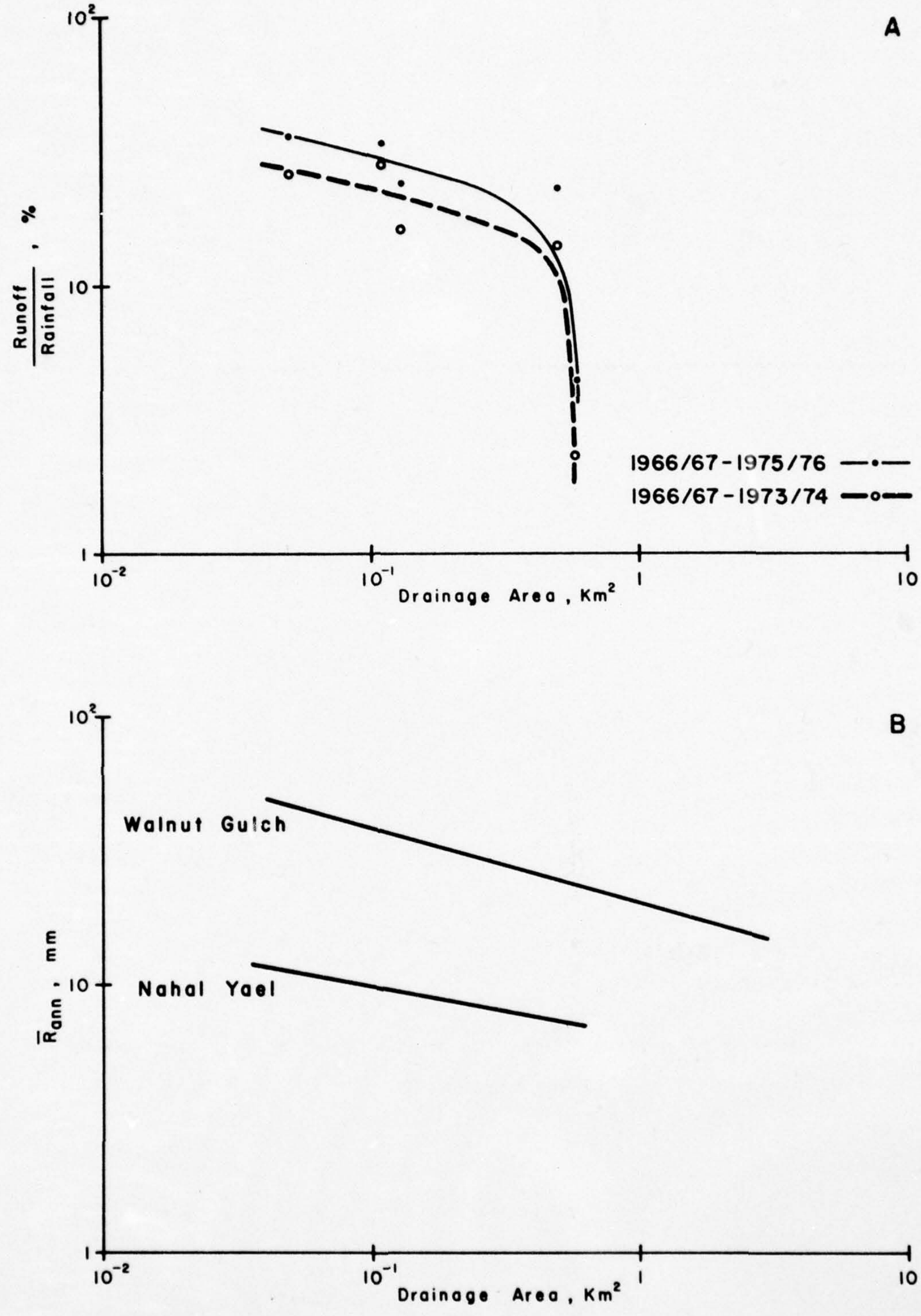


Figure 3:2

A. Change of runoff/rainfall ratio with catchment area, Nahal (=wash) Yael, southern Israel (data from Schick, 1977).

B. Relation of mean annual runoff to watershed area in Walnut Gulch (semiarid, southeastern Arizona; Osborn & Renard, 1970) and Nahal Yael (extremely arid, southern Israel; data from Schick, 1977).

4. There is a wide discrepancy between the amount of sediment, measured and calculated, which passes the apex of the alluvial fan and/or beyond it into a larger trunk stream (Table 3:1).
5. Median size of material constituting the inner channels is two to three times larger than that sampled in transit.
6. Most of the suspended load fractions are not represented on present-day hillslopes. This is also the case for vast areas in southwestern Arizona. Present-day streams, operating under an arid climatic regime, obtain most of their finer fractions from windblown clastics and destruction of alluvial terraces.

Net aggradation, alluvial fan, 27 April 1967 to 14 November 1973, as determined by cross-section surveys	10.57 m^3	21 tons
Sediment inflow, station 02, same period (events 7A, 7B 10):		
(i) suspended	390 tons	
(ii) bedload (½ added)	195 tons	585 tons
Sediment outflow, station 01, as above:		
(i) suspended load	176 tons	
(ii) bedload (½ added)	88 tons	264 tons
Reduced aggradation on fan,		
total load		321 tons
bedload only		107 tons

Table 3:1 Tentative sediment budget for the Nahal Yael alluvial fan (after Schick, 1977). Stations 02 and 01 are at the apex and toe of alluvial fan, respectively.

3.2.2 LOCALIZATION OF INTENSIVE FLOODS - A GENERAL CHARACTERISTIC OF ARID REGIONS

Most runoff-producing rainfall events are smothered in space and time. Two studies, one of a typical thunderstorm-affected area in southern Arizona

(Osborn and Renard, 1970; Osborn and others, 1971) and the other of a characteristic frontal rainfall of southern Israel (Sharon, 1972), lead to some similar general conclusions:

1. Most of the runoff is generated by local rainfall cells, ranging between 0.5 and 10 km in diameter. The larger cells within this range are typical to the semiarid climate in southeastern Arizona. In the arid regions, such as southern Israel and southwestern Arizona, diameters of 0.5 to 5.0 km would apply.
2. There is a high variability in intensity, amounts and duration of rainfall in time and space.
3. There is a rapid change in intensity and amount from a "center" of a rainfall cell to the margins.

The above conclusions are corroborated by some indirect geomorphic evidence, as demonstrated by Wolman and Gerson (1978). In arid regions, there is a rapid increase of mean channel width with catchment area of up to 10 to 50 km^2; the rate of increase becomes less, until there is practically no increase of width for channels draining more than 100 km^2. Effective catchment, then, coincides with storm cell size, even for extreme events.

It is generally accepted that abrasion is the major factor in reduction of gravel size of graded and degrading streams (Mackin, 1963). Sorting is effective mainly on the smaller fraction with granules, sand and fines winnowed selectively.

The volume of sediment and sediment discharge do not decrease downstream mainly due to the following reasons:

1. Coarse, as well as fine, sediments are added to the channel, contributed by adjacent hillslopes and tributaries.
2. The rate of abrasion producing fine materials, by weathering and fine chipping, is not significant, either in itself or relative to the rate of addition of coarse gravel mentioned above.

The above is true mainly in stream channels receiving gravel from rocky terrains. Downstream from mountain fronts, in alluvial piedmont areas, there are two possible results:

1. No appreciable addition of gravel from older alluvial fills. A sharply increasing rate of decrease in size would occur in this case. This represents active fan deposition.
2. A continuous (in space and time) contribution of gravel from old fills to active channels, by gullying and bank erosion occurs in this case. There may be no change of rate of size decrease downstream from the active fan area. Sorting will become a major processes while coarser sediment is left behind and finer clastics reach fans toe.

It is this latter trend that is more characteristic to most arid regions, where contribution of clastics from older alluvial fills regulates size distribution the same way it does in rock drainage basins.

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4.0 PRODUCTION, TRANSPORTATION AND DEPOSITION OF GRAVEL

by Ran Gerson and Larry Mayer

4.1 PRODUCTION OF GRAVEL

4.1.1 GENERAL

Production of debris, in terms of both size and rate of delivery, is dependent on several factors:

1. Initial rock structure - joint spacing, bedding, foliation.
2. Rates of removal (erosion) and exposure of fresh rock.
3. Weathering of rock and debris.

Rates of removal of debris and weathering are the factors that determine the deviation of footslope particle size distribution from joint-block size distribution.

Gravel-sized materials are produced mainly by mechanical weathering, acting upon existing jointed rock, whereas granules to fines are produced mainly by chemical weathering and abrasion during transport. This is generally true regarding most igneous and metamorphic rocks. In other lithologic environments, like mudstones and some sandstones, mechanical weathering may produce fines or sands and the effects of chemical weathering are negligible.

Sampling of debris at the foot of a hillslope or in headwater stream channels reflects a biased size distribution towards the coarser fraction lagging behind as bed load, while most of the sandy and silty fractions are winnowed by wash.

4.1.2 HILLSLOPES - DEBRIS REMOVAL FROM BARE ROCK AND TALUS MANTLE

Hillslopes in deserts are controlled, in terms of the debris removing mechanisms, mainly by the following processes:

1. Wash. Granule to fine materials are washed downslope by runoff.
2. Flow. Material en mass is rapidly moved downslope, as debris flows, mudflows and less frequently, landslides.
3. Fall. Gravity controlled processes, typical to steep rock free face.
4. Gullying. Affecting mainly talus slopes that are destroyed or eroded, usually after some extreme event or because of an environmentally irreversible change.

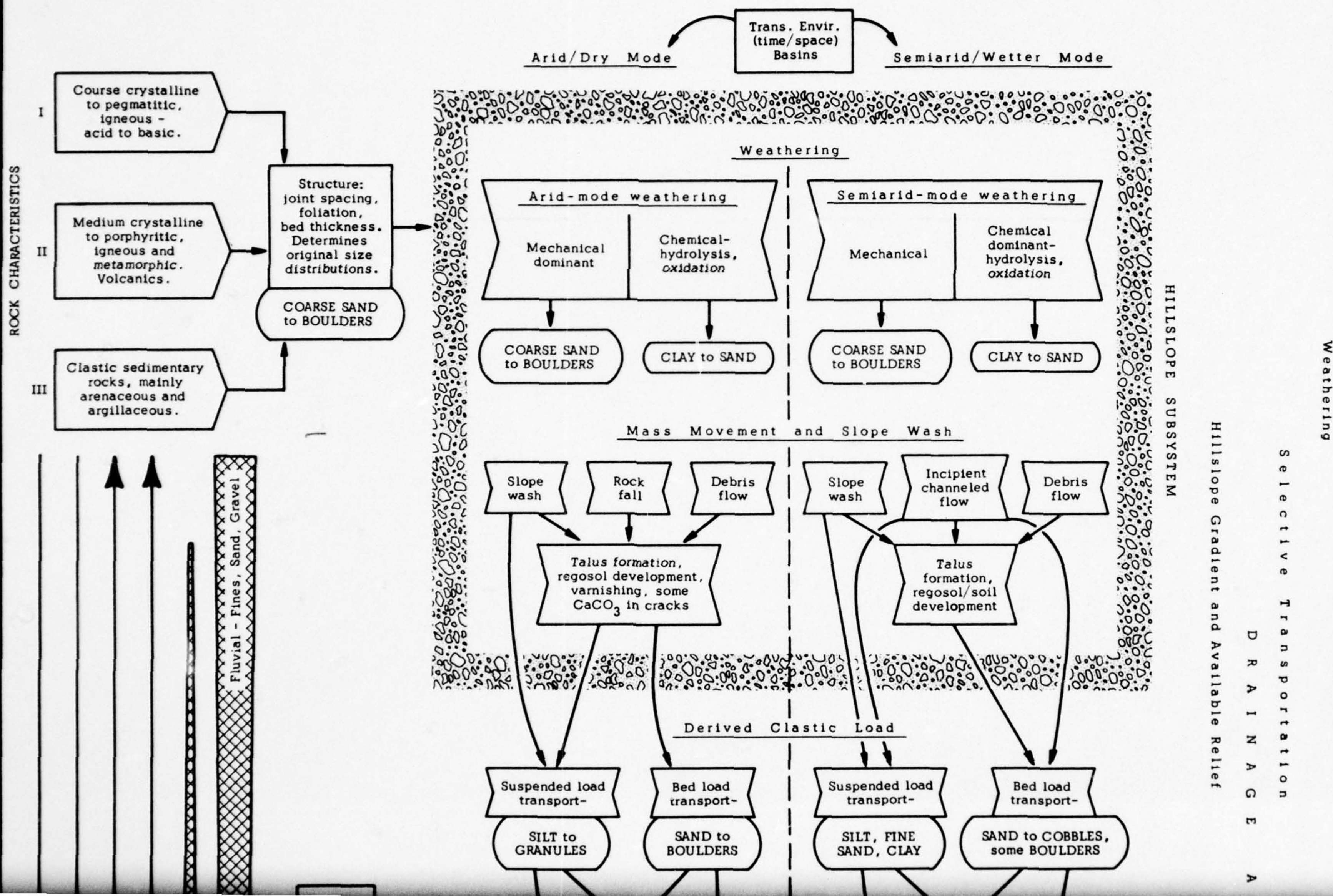
Wash and gullying may affect hillslopes, or portions of them, in all rock types and gradients. Wash carries mainly granules to sand sizes. Only where unconcentrated wash is converted into channeled flow in gullies, may pebble size be involved in movement. Flow en mass, especially debris flows, can transport every available material size, including very large boulders.

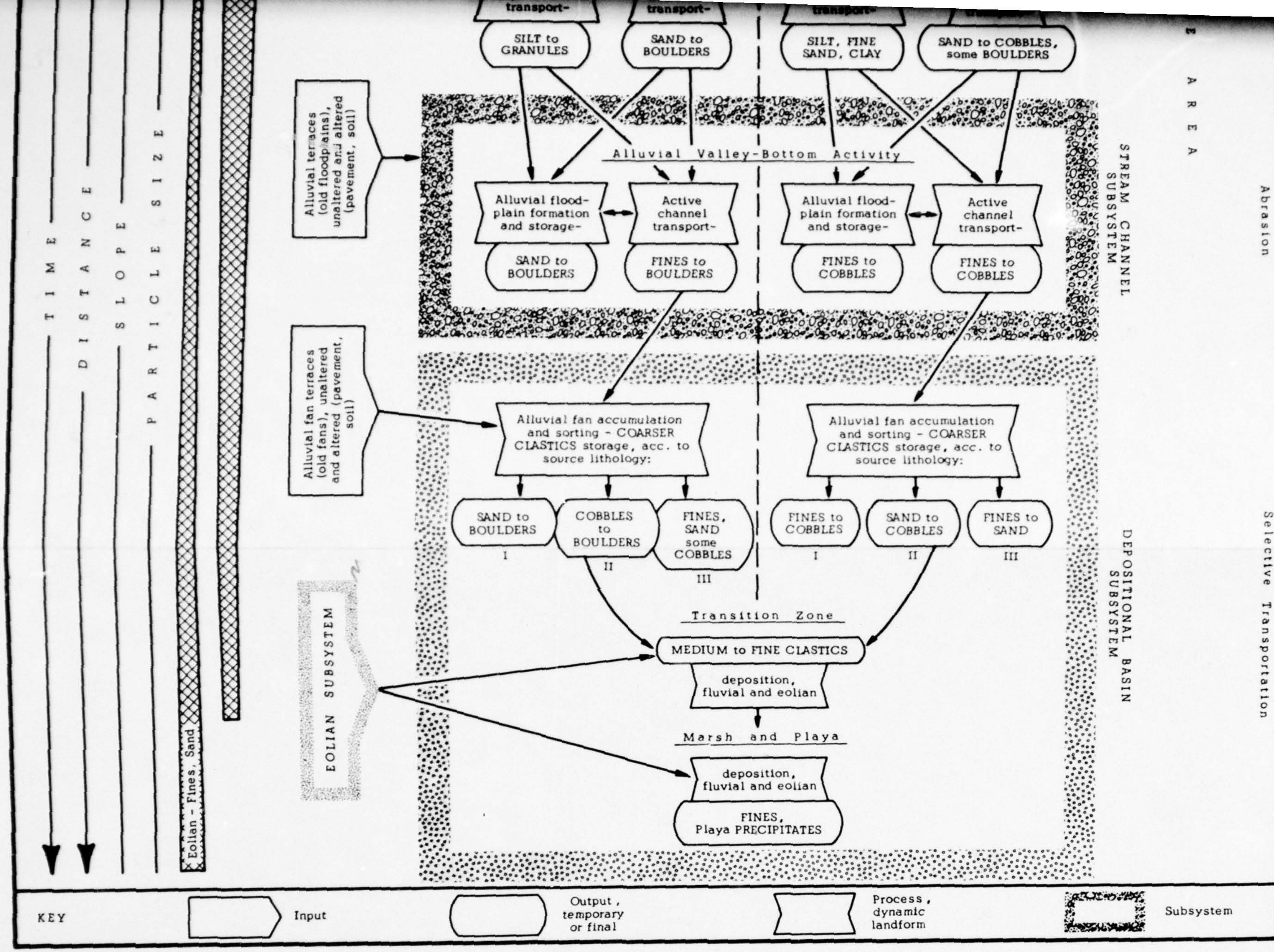
There are only a few studies on the delivery of debris from hillslopes to stream channels in arid regions, and all deal with wash load, granules-to fines-sized sediments (Yair and Klein, 1973; Yair and Lavee, 1974, 1977; Gerson, 1977).

4.1.3 DEBRIS FLOW - A MECHANISM OF PRODUCTION AND TRANSPORTATION OF COARSE GRAVEL

Debris flows are masses of coarse-to fine clastics, with a relatively small amount of water, generated on talus-mantled hillslopes and may occur along first-to-third order streams. They are dense and viscous and can transport particles of any available size. Most debris are poorly sorted flows containing silt to boulder size in an ungraded fashion. Sorting of old fossil debris flows improves with time as the finer, muddy-sandy matrix is winnowed (Figure 4:2).

ORIGIN and DISTRIBUTION of GRAVEL in STREAM SYSTEMS of ARID REGIONS





transport-
transport-
transport-
SILT to GRANULES
SAND to BOULDERS
SILT, FINE SAND, CLAY
SAND to COBBLES, some BOULDERS
A R E A
Abrasion
STREAM CHANNEL SUBSYSTEM
Alluvial terraces (old floodplains), unaltered and altered (pavement, soil)
Alluvial Valley-Bottom Activity
Alluvial flood-plain formation and storage-
Active channel transport-
SAND to BOULDERS
FINES to BOULDERS
FINES to COBBLES
FINES to COBBLES
Alluvial fan terraces (old fans), unaltered and altered (pavement, soil)
Alluvial fan accumulation and sorting - COARSER CLASTICS storage, acc. to source lithology:
SAND to BOULDERS
I
COBBLES to BOULDERS
II
FINES, SAND some COBBLES
III
FINES to COBBLES
I
SAND to COBBLES
II
FINES to SAND
III
DEPOSITIONAL BASIN SUBSYSTEM
Selective Transportation
EOLIAN SUBSYSTEM
Transition Zone
MEDIUM to FINE CLASTICS
deposition, fluvial and eolian
Marsh and Playa
deposition, fluvial and eolian
FINES, Playa PRECIPITATES
T I M E
D I S T A N C E
S L O P E
P A R T I C L E S I Z E
Eolian - Fines, Sand
KEY
Input
Output, temporary or final
Process, dynamic landform
Subsystem

Figure 4:1

Figure 4:2 Large granitic boulders in a Holocene debris flow, Sheep Mountain, southwestern Arizona.

Debris flows are associated with high-intensity rainfall events. Commonly, they are triggered by rockfall at a scarp above a partly saturated talus and develop into a debris flow over the moistened talus. Debris flows, lubricated by some silt and sand derived from the primitive soil profile developed in a talus, are an essential mechanism in the activity of a talus. Areas or stripes that have been affected by debris flows are usually stabilized for 10^3 to 10^5 years until they (both scarp and talus) recover to a condition optional for another event.

Debris flows are common to the following geomorphic environments:

1. Hillslopes having a scarp facet above a talus facet. The scarp should be composed of unstable to metastable joint blocks.
2. A well-developed, continuous talus slope. The talus should have at least an incipient soil profile (regosol) containing some fines and sand underneath the top talus pavement. These may have been developed or introduced into the soil profile during the time when climates were wetter than the present.
3. Areas subject to occasional intensive rain storms.
4. The upper portion of the talus should have a gradient of at least 20°.

These conditions are best met in several lithostructural environments, although they are not restricted to them:

1. Volcanic terrains, in which basaltic scarp-forming jointed cap rock overlies other, slope-forming types of rocks (such as quartz-latite in the Painted Rock Mountains, southwestern Arizona (Figure 4:3); volcanoclastic rocks, as in the northern part of the Aguila Mountains, southwestern Arizona.)

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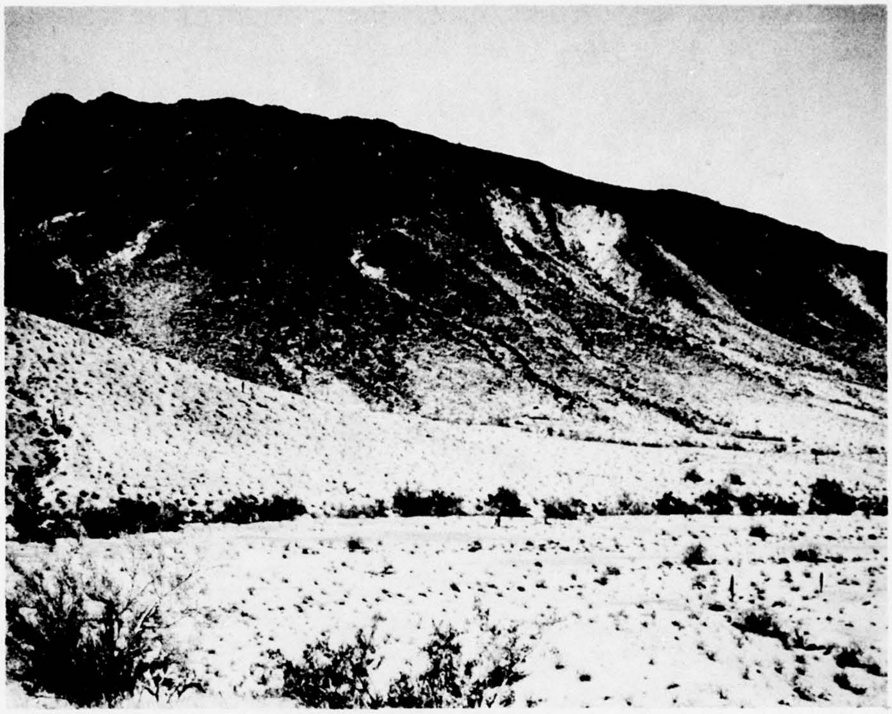
Figure 4:3 Holocene debris flows in the Painted Rock Mountains, southwestern Arizona. Flow levees are composed of boulders derived from basalt caprock overlying quartz latite.



A. General view.

B. Debris flow levee.

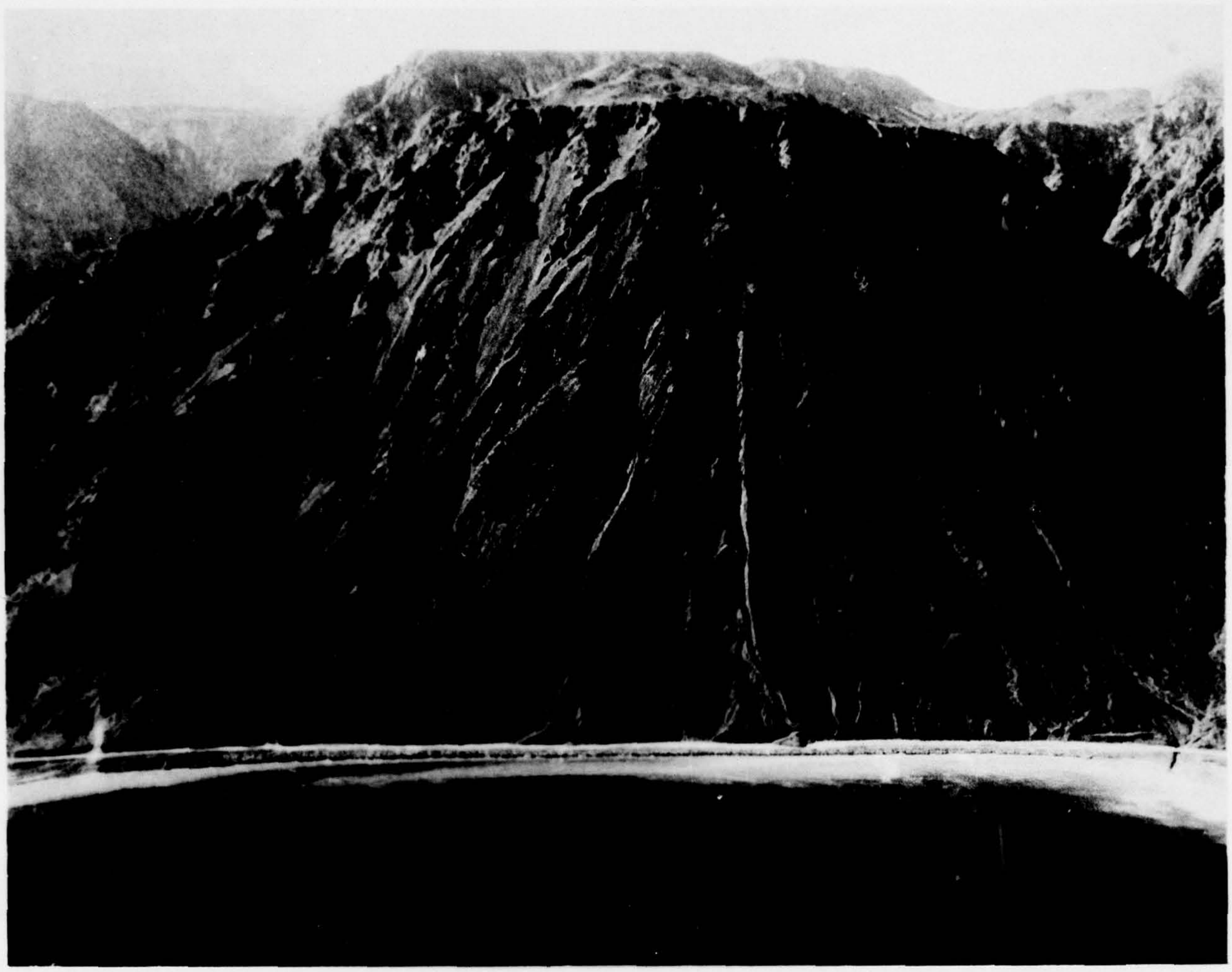


Figure 4:4 Recent debris flows on active talus, eastern Sinai. The lithology is dioritic gneiss. The latest event, covering the Longshore Elat-Sharm El Smeikh Road, occurred Feb. 19, 1975.

2. Terrains underlain by weathered coarse crystalline rocks, such as granites and quartz monzonites (in the Gila Mountains, southwestern Arizona).
3. Densely jointed rocks or rock sequences, where the rocks are highly shattered, as is the case of a latite-volcanoclastic-rhyolite sequence in the western side of the Aguila Mountains (southwestern Arizona) or metamorphics in east Sinai (Figure 4:4).
4. In actively eroding plateaus, where resistant scarp forming limestone or dolomite cap rock overlie chalks or sandstones, as is the case in southern Israel and central Sinai.

In summary, a combination of scarp-steep talus, weathered or shattered talus-forming materials and intensive rainstorms is best for triggering and moving flows of unsorted debris.

Accumulation of fine weathering and windblown materials and the occurrence of triggering rainfall events are time-dependent. It is clear that every given strip of a debris flow prone talus accumulates higher probability of failure with time. Both regosol development and the very extreme event necessary for triggering another extreme debris flow occurrence did not have the required duration.

Debris flows are exhausted by decrease of gradient in the lower concave portions of hillslopes and loss of water and friction, both internal and with its bed. Most debris flows do not make it to the base of the slope, but many do.

The density and viscosity of debris flows, and the high friction with their boundaries, lead to the formation of debris flow levees. These debris flow

levees are the main features left, whether most of the inner flow mass left its track or slowed down in it and stayed there. Subsequent erosion usually takes place in debris flow paths or at the contact with the levees.

The distance of debris flow deposition is dependent on several factors:

1. Climate. The more humid it is, within the arid-semiarid range, larger the amounts of fines are present and higher rainfall intensities are anticipated.
2. Watershed morphometry. Steep and long hillslopes, narrow and steep valley bottoms, and large watersheds, draining 20 to 50 km^2.

These factors, in addition to highly weatherable or shattered materials, will promote debris flows and enable them to transport their sediment to an appreciable distance within a watershed and along alluvial fans. An example of an area where these factors are present and promote debris flows that transport coarse material well into the depositional basin is Death Valley (Denny, 1965; Hooke, 1967). On the other hand, vast Basin and Range areas in southwestern Arizona and central Nevada that have narrow mountain ranges and small watersheds, and are under an arid climate, are not capable of generating debris flows that can transport coarse gravel more than 0.5 to 1.0 km off the mountain fronts (see Section 4.4).

4.1.4 SIZE DISTRIBUTION OF HILLSLOPE GRAVEL

4.1.4.1 <u>Joint Spacing</u>

Joint spacing reflects the size range of potential rock blocks and may differ greatly from one site to the other, either within the same lithologic province or between lithologies. Usually, joint blocks size distributions have good

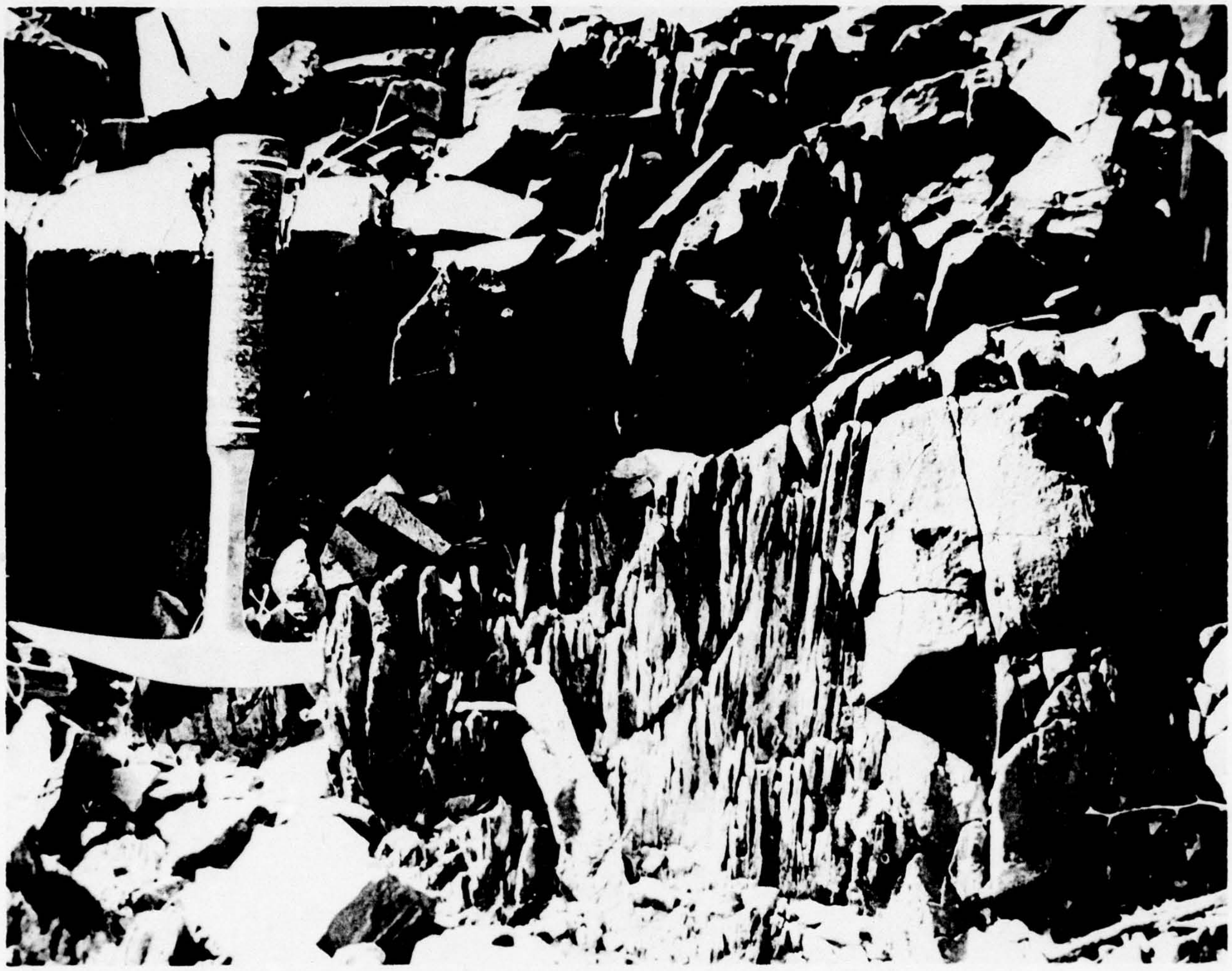


Figure 4:5   Jointed rocks in the Mohawk Mountains, south-western Arizona.

Figure 4:6 Heterogeneity of structure of bare rock and texture of talus mantle. Granite Mountains, southern California.

sorting, unrelated to the joint density at a site (Figure 4:5). This may reflect a quite homogeneous stress-strain response, marked to some extent by subsequent mechanical weathering. However, there is no generalization and there are many exceptions. One example is illustrated in Figure 4:6. Mechanical weathering is presumably the usage for the finer trail of the size distribution. The distribution in different rock types has the same general shape, regardless of site (Figure 4:7). It has to be kept in mind that there may be a bias in sampling joints; micro-joints and fractures can also occur and be a penetrative feature, yet these would not be sampled. This is especially true where these fractures coincide with mineral boundaries in coarse-grained granitic rocks.

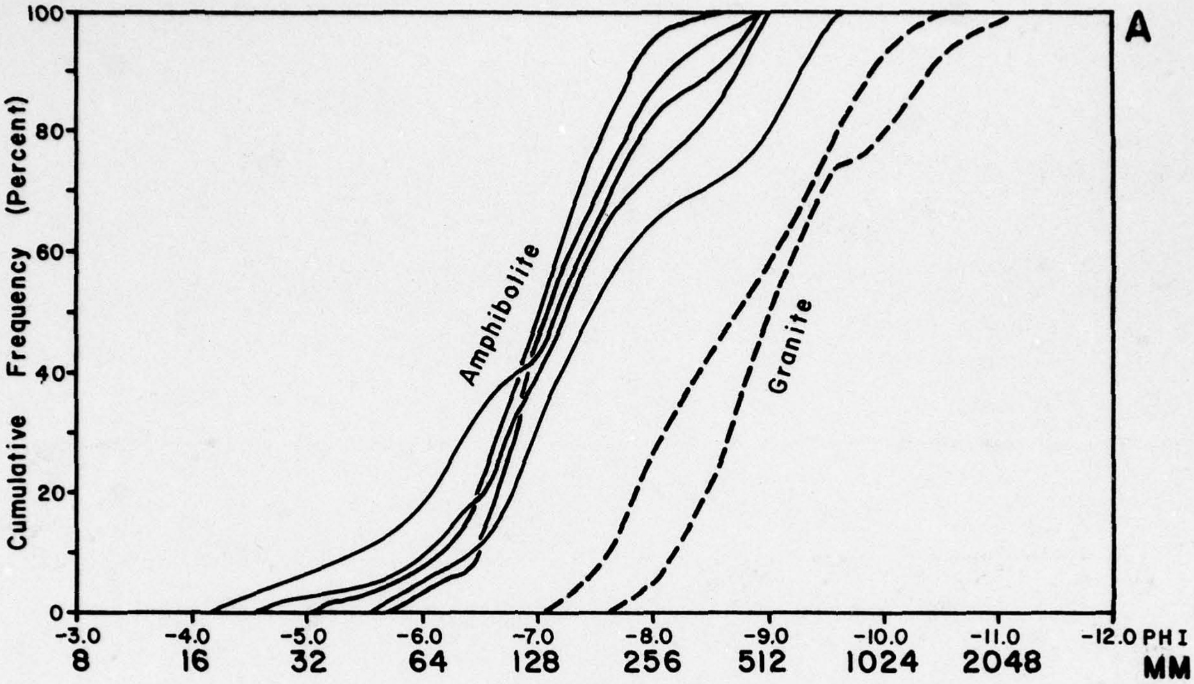
4.1.4.2 Talus Particle Size Distributions

Talus gravel size distributions reflect some mechanical fracturing at most sites, but essentially the material in non-debris-flow facets is well-sorted in most rocks that are resistant to chemical weathering. This is not the case in coarse crystalline granitic and quartz monzonitic rocks (Figure 4:7). Poor sorting and a distinct, finer gravel tail are apparent, as a result of weathering. The susceptibility of granitic rocks to weathering is the main reason for the appearance of pebbles in a talus where they originated from native rock jointed only to cobble and boulder sizes.

4.1.4.3 Particle Size Distribution in Debris Flow Remnants

Figure 4:8 illustrates typical features of debris flow gravel size distributions. These factors include:

1. Poorly sorted gravel ranging from small pebble to large boulders. This does not include some 10 to 30% of finer (sand and mud) materials that were



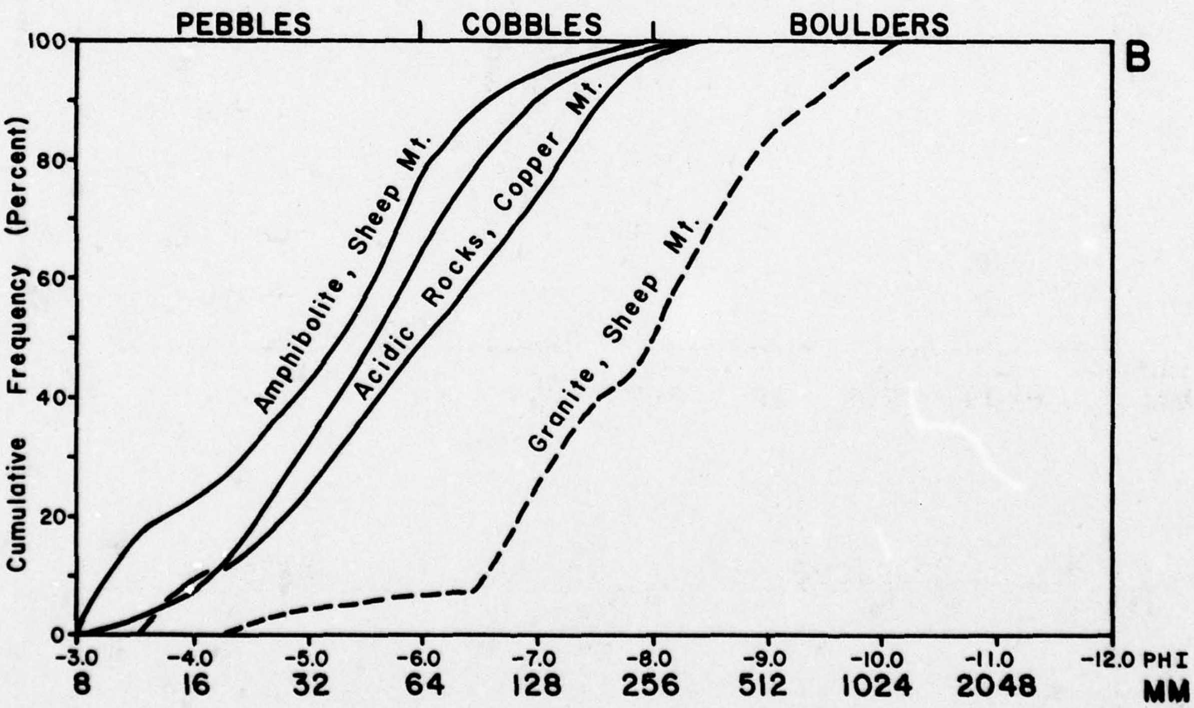


Figure 4:7

A. Joint spacing distribution in granite and amphibolite, Sheep Mountain, southwestern Arizona.

B. Particle size distributions of talus mantles in granite and amphibolite, Sheep Mountain, southwestern Arizona, and Copper Mountain, southern California.

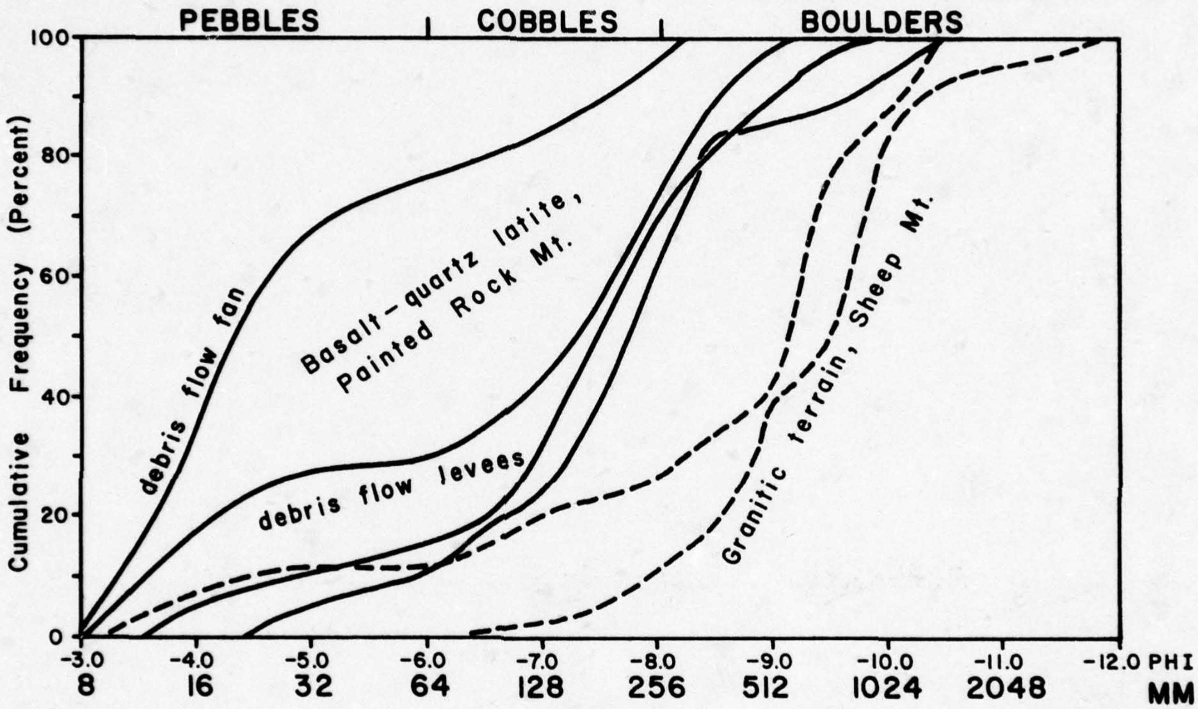


Figure 4:8 Particle size distribution of debris flow remnants in granitic and basaltic terrains (Gila Mountains and Painted Rock Mountains, southwestern Arizona, respectively).

washed away from the debris flows lobes during the Holocene and historic times.

2. Debris flows in granite may be larger in their coarser fractions, but owing to weathering they may include 2 to 10% of small cobbles and pebbles.
3. Other sediments, either stream channel or fan deposits, are by far finer grained (Figure 4:8), and better sorted.
4. Along the debris flows remnants there is some change in particle size. This change is not systematic and cannot be attributed to the size fluctuations within a debris flow.
5. Comparison of joint-block and debris flows site distributions in the Sheep Mountain area shows the similarity between the two. Again, due to weathering pre- and post-flow, there is a finer-sized tail in the debris remnants.

4.1.5 THE EFFECTS OF LITHOLOGY ON PRODUCTION OF DEBRIS

Generally, the weatherability of rocks is related to their mineral composition, texture and cohesiveness. In arid regions, mineral compositon is usually of minor importance because of the scarcity and low chemical aggressiveness of rainwater. As a result, we cannot easily relate erodibility of most common rock types to any rock classification based on mineral composition. The result is that we do not have a definite trend in erodibility and derived clastic characteristics related to rock classification.

On the other hand, joint density (largely a result of outside stresses and not a completely rock-type related variable) was found to correlate well with erodibility.

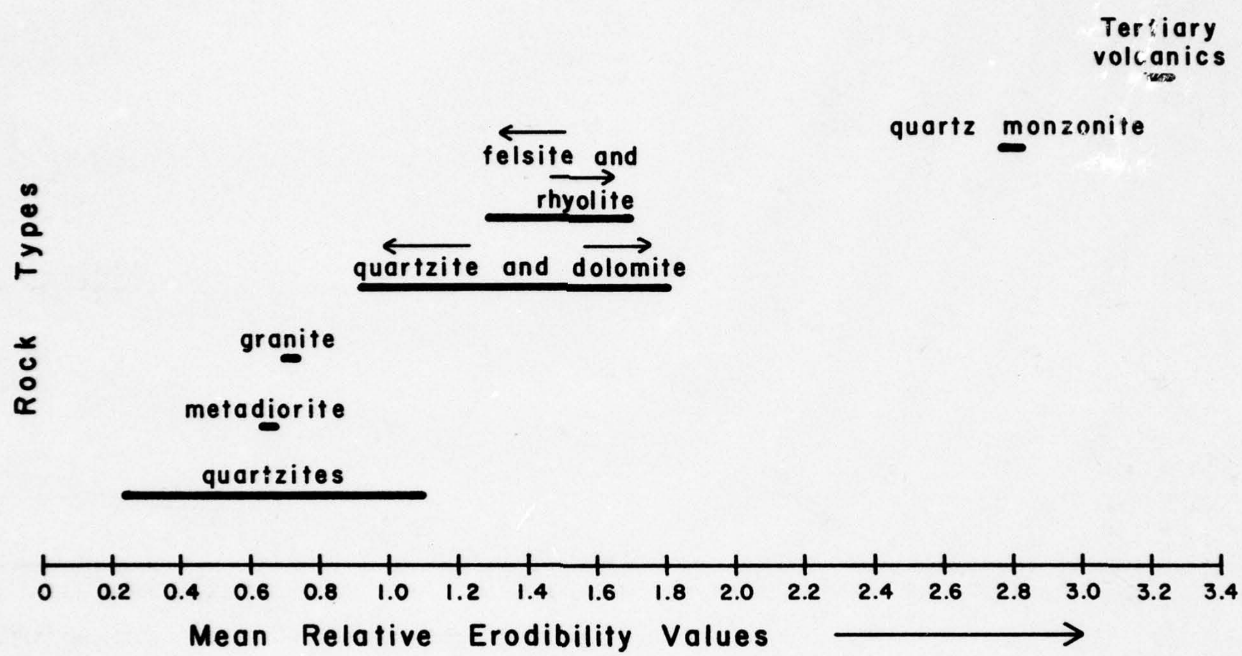


Figure 4:9 Erodibility and rock type relationships (data from Hooke and Rohrer, 1977).

A list of rock erodibility for Death Valley (Hooke and Rohrer, 1977) demonstrates the relationship between joint spacing and erodibility (Figure 4:9):

Lowest erodibility -	Quartzite
	Metadiorite
	Granite
	Quartzite and dolomite
	Felsite
	Dolomite and argillite
	Rhyolite
	Dolomite
	Quartz monzonite
Highest erodibility -	Tertiary volcanics

Comparing this jointing-based erodibility list with arid zone weatherability shows that there is no straightforward correlation between them. For instance, the more weatherable igneous rocks, such as coarse crystalline granite or quartz monzonite do not appear to be highly erodible on the above list. Rhyolite, a rock highly resistant to chemical weathering, is very erodible where densely jointed.

Most fissile or fractured rocks are gravel producing on hillslope and most of the watersheds built of them deliver gravel to the depositional basin.

There are several rock types that produce gravel at the mountainous watersheds but deliver, due to their high weatherability, relatively little amounts of pebble to boulder sized gravel to the depositional basin.

1. Coarse grained granite.
2. Coarse grained quartz monzonite.
3. Hard, indurated sandstones.

On the other end of the spectrum there are two rock types that produce gravel closely related to initial joint block size, and very little grandules and sand.

1. Quartzite.
2. Basalt.

Between these two groups, so unrelated within themselves, all other mechanically resistant rocks appear. Their order of gravel/sand+fines ratio is dependent mainly on rock texture and joint spacing.

4.2 TRANSPORT OF SEDIMENT IN STREAM CHANNELS OF ARID REGIONS

The subject of sediment transport is most conveniently treated from two points of view:

1. The characteristics of the transported sediment such as size distribution and its relationships with the hydraulic variables of the flowing water.
2. The amounts of transported sediment, related to sediment characteristics and watershed and flow variables.

Study of both viewpoints involve empirical data and measurement while transport is taking place.

Figure 4:1 is a flow diagram illustrating geomorphic activity in arid watersheds and the general trends observed in sediment size as it is being produced, transported and deposited by different processes down the fluvial system. Spatial and temporal climatic changes, from a semiarid mode of operation to an arid mode, actually did occur in many watersheds. This climatic change would cause changes in sediment yield and particle size distribution in all fluvial subsystems. Figure 3:1, illustrating the various variables acting upon and within the fluvial system, also indicates how climatic changes may affect various parts of the fluvial system and resulting sediment output, both in character and yield.

4.2.1 APPROACHES TO SEDIMENT TRANSPORT IN STREAM CHANNELS

There are 10 variables involved in the stream flow - sediment transport (Maddock, 1969):

1. Discharge of water.
2. Discharge of sediment.
3. Size composition of the moving sediment.
4. Size composition of bed material.
5. Fall velocity of a characteristic sediment particle.
6. Width.
7. Depth.
8. Velocity.
9. Slope.
10. A characteristic of the pattern of streamflow.

For coarse alluvial sediments in gravelly channels, variable 5 may be dropped and variables 3 and 4 combined. For alluvial channels in arid regions, we still miss most data related to sediment in motion. No reliable data are available for streams carrying gravel in arid terrains (see Chapter 3).

Various empirical bed load transport equations were offered during the last century. Most of them deal with sand and granules and involve dynamic variables such as water discharge, some specific velocities, water surface slope and depth of flow. Graf (1971) groups the different approaches to bed load transport thus:

1. Shear stress relationships (like the DuBoys equation).

2. Discharge relationships (like the Schoklitsch equation).
3. Statistical considerations based equations (like the Einstein equation).

Another approach, forwarded by Leopold and Emmett (1976) and Emmett (1976) is based on Bagnold's (1966) stream power equation. This approach successfully related measured bed load transport rates for bed load materials of different median sizes. The Leopold and Emmett method, based on experiments with sand and granule sizes, has been expanded to cobble and boulder sizes by Inbar (1977).

Most equations of this sort are empirical or semiemperical and rely on experimental determination of coefficients. Their use is limited to similar hydraulic and sedimentologic conditions as originally used in their development. Only the Leopold-Emmett method and group of curves for different sizes can be immediately applied for universal use. Unfortunately, the Leopold-Emmett curves are completely dependent on stream power which excludes their use in ungauged arid region streams.

A completely different approach, known and practiced for many years in the non-arid environments, is the experimental assessment of total sediment load by using reservoir traps, and relating the total amounts to climate (Langbein and Schumm, 1958; Wilson, 1973) or catchment area (Brune, 1948; Hadley and Schumm, 1961; USDA, 1973). Studies using these approaches are based on data from semiarid through humid environments and from terrains mantled by erodible materials (fines and sand as major soil fractions). The elements used in these different equations are effective precipitation, runoff rates, maximum yearly peak discharge, catchment area, topography, percentage of vegetational cover, hourly or total runoff. No data for these variables are available for the watersheds dealt with in the present report. Since most mathematical

sediment yield models are based on runoff generating models, one has still to wait for data accumulation of runoff for small arid watersheds. These, which may fairly account for suspended sediment load, combined with discharge, depth, slope and width data used in the Leopold-Emmett method for bed load, may yield the necessary basis for predicting sediment yield in ungauged arid regions.

As far as we are aware, there have been very few watersheds studied in the arid regions. Results from one of these, Nahal Yael, may serve as an example of the uncertainties and complexities involved. Nahal Yael experimental watershed is located near the town of Elat, southern Israel. Mean annual precipitation is 32 mm. Catchment area is 0.6 km^2, available relief is 150 m and exposed lithologies include amphibolite, diotite, schist, granite and various dikes. Measurements of rainfall, streamflow, sediment transport and deposition and changes in geomorphic features have been conducted during the last 10 years. Table 3:1 shows a tentative sediment budget for Nahal Yael during a period of six years (Schick, 1977). Studying the table, one is struck by the discrepancy between sediment inflow into the fan (through station 02) and sediment outflow from the fan (station 01) plus net aggradation on the fan.

Large discrepancies were also found in other studies in semiarid regions. Examples are the Cheyenne River basin (Hadley and Schumm, 1961) Piceance basin in western Colorado (Hadley and Shown, 1976) and Arroyo de los Frijoles, New Mexico. In all cited watersheds, delivery ratio (the ratio between sediment yield by a watershed and the total material eroded from the watershed) is low. Lack of accurate monitoring, lack of a long enough period of measurements and

the necessity of including extreme events in the analysis are a few of the reasons for this situation.

An overall conclusion from the foregoing review is that we still cannot predict sediment yield for the arid regions and, hence, have no means to project estimates back into the past (the Holocene and late Quaternary) when the upper parts of basin fills were deposited.

4.2.2 TRANSPORT OF SEDIMENT IN STREAMS OF ARID REGIONS

Sediment is transported in stream channels in two modes:

1. Suspension - suspended load.
2. Touching the bed most of the time - bed load.

There is an exchange between suspended and bed loads, effecting mainly particles of sand size. A practical distinction between materials carried in streams is that gravel is transported as bed load and fines (silt and clay) as suspended load.

As presented in Section 4.2.1, very few data are available for gravel in motion for arid region stream channels. More is known about suspended load for such streams. Hence, field examination and project to generally similar terrains has to rely mainly on observations and measurements of stream channels between flows. In most terrains underlain by cohesive brittle rocks, bed material is mostly gravel. In many cases, only small amounts of sand and fines are found in channels within the erosional portion of the alluvial system. Most sands and silts are winnowed as suspended load from the erosional terrain and are deposited in the depositional basin. In

other, rather frequent cases, relative amounts, or the ratio G/F between gravel and fines, may be close to 1.0 in bed material in headwater reaches and is close to zero in the center of depositional basin. This ratio is not the same in sediment transport rates throughout the fluvial system. It may range between 0.8 and 0.3 in many arid mountainous watersheds underlain by gravel producing rocks, but still will get close to zero nearing the center of a wide depositional basin.

4.2.3 ENTRAINMENT OF GRAVEL IN STREAM CHANNELS

Although clastic transport is considered to be of a stochastic nature, the DuBoys equation may serve as an approximation for initiation of movement:

$$\tau = \gamma RS$$

Where γ = specific weight of water; R = hydraulic radius; S = energy slope represented by water surface slope. τ, then, is an average value of boundary shear stress, or tractive force over the channel bed.

Since we are dealing with relatively wide channels, $\bar{d}$ (mean depth) is a reasonable approximation for R. γ is, in most terrains, close to 1.0, as suspended load does not change weight and viscosity in any effective manner.

There exists a large volume of data relating particle size to tractive force. Figure 4:10 is a compilation of data and curves presented by various authors, based on observation and experimentation. Many empirical studies used materials of nearly uniform sizes, whereas others dealt with mixtures and utilized median or mean sizes as representative. Inspection of Figure 4:10, relating intermediate particle diameter to tractive force,

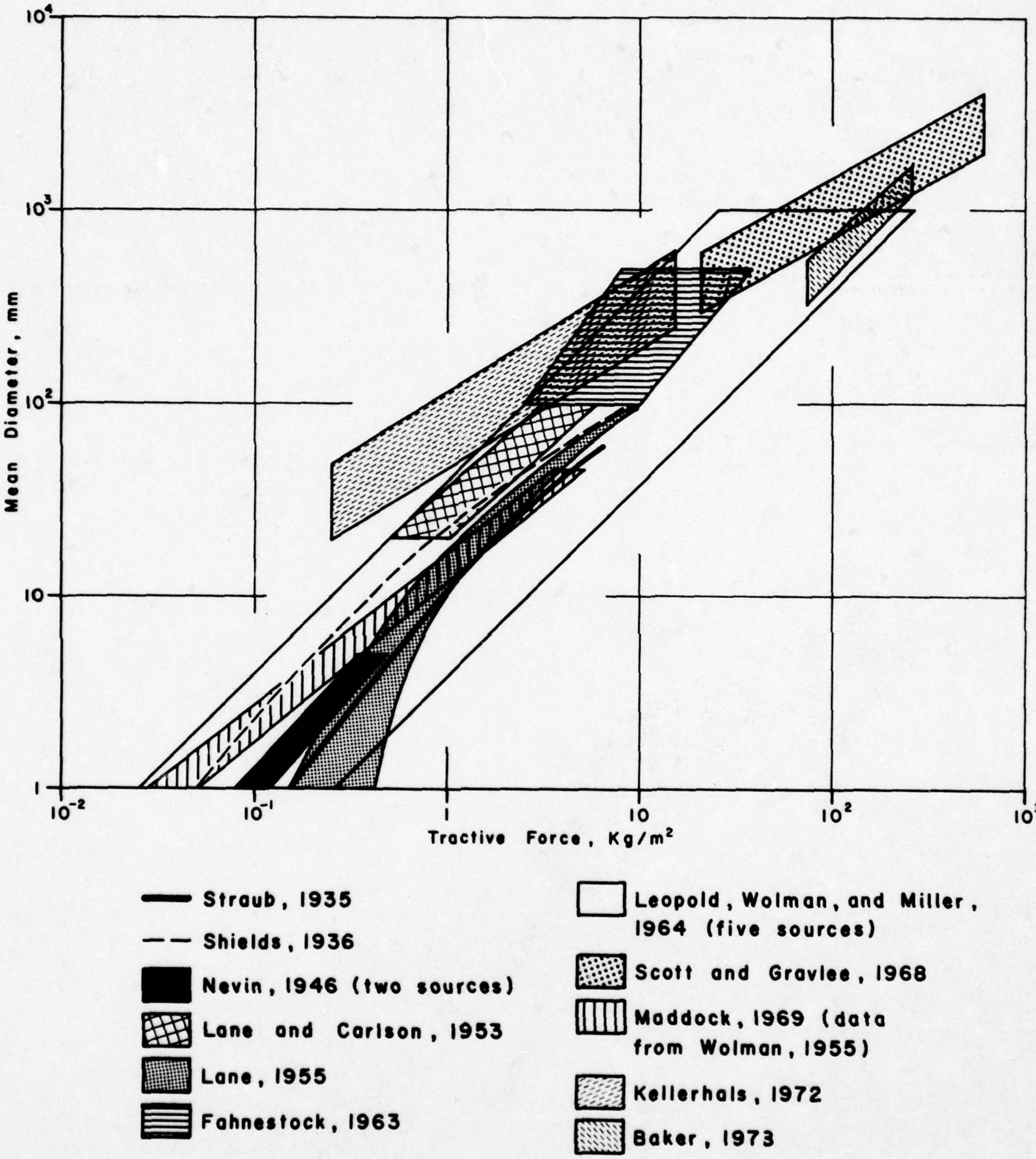


Figure 4:10 Relationships of intermediate particle diameter and critical tractive force for coarse sand and gravel

shows that a wide range in size exists in most empirical studies of incipient motion of coarse sand to large gravel:

$$D \propto \tau_c^{0.5} \text{ to } D \propto \tau_c^{1.0}$$

D is intermediate particle diameter and τ_c is critical tractive force. It seems, though, that for the larger diameters, >10 mm, $D \propto \tau_c^{0.50}$ to $D \propto \tau_c^{0.75}$ is applicable. This may be in accordance with studies by Rubey (1937) and Wolman and Brush (1961), that show incipient motion of larger particles appear to be more velocity-dependent than tractive-force-dependent.

Motion is affected by size, orientation, packing and turbulence and, hence, is probabilistic in nature. The range of flows typical to arid regions stream channels is so wide (see Section 3.2) that armoring and sorting are upset by extreme flow events that render the channel to behave in a deterministic fashion, whereby its sedimentary features are determined by the action of high enough tractive forces to move particles of almost every available size.

In terms of mean velocity, mean particle size relationships, studies have repeatedly shown that:

$$\bar{V}_c \propto D^b; \quad D \propto V_c^f$$

Where: V_c = critical mean flow velocity

D = intermediate diameter

b = an exponent, ranging between 0.30 and 0.50

f = an exponent, ranging between 2.0 and 3.3

Examples are illustrated in studies by Hjulstrom (1935), Nevin (1946), Sundborg (1956), Fahnestock (1963), Helley (1969), Novak (1973) and Bogardi (1974).

In view of the relationship:

$$\tau_c \propto V_c^2$$

it is possible to use either variable, but since velocity in ungauged streams is more difficult to estimate (because of Manning's n), it is more efficient to use tractive force for prediction of movement of gravel.

4.2.4 CHANGES IN PARTICLE SIZE DISTRIBUTION IN FLUVIAL SYSTEMS

As fluvial gravel proceeds downstream, two definite trends are present:

1. A general decrease in size, as may be represented by mean, median and maximum sizes.
2. A decrease in spread of size around the mean or median, termed sorting, and expressed statistically as the standard deviation.

These trends are due to two groups of processes:

1. Wear, by weathering, breakdown and abrasion.
2. Selective transportation, related to various processes and their magnitude.

Because of the difference in the ratio between the amounts of water and sediment involved and the large difference in slope, there are some processes active on hillslopes different from those acting in stream channels. The results are expressed in particle size distribution, and its change in time and space.

Selective transportation is a dominant feature in fluvial systems carrying gravel, sand and fines, especially in arid regions where flows are sporadic and exert high shear stresses. We find that wash, carrying fines and sand remove them from exposed portions of hillslopes and winnow them from confined reaches of stream channels. Hence, one may expect the ratio between gravel and fines, G/F ratio, to decrease downstream. This is both because of the winnowing process and the general decrease in size downstream. In the arid regions, where most sediment samples are collected between floods, there is a wide discrepancy between bed material and total sediment load in terms of size distributions. Two examples may serve to illustrate this point. In Nahal Yael, southern Israel, the ratio in the dry main channel is $\frac{G}{F} \simeq 4.0$, while the average ratio during sediment transport in low-to-medium magnitude flow events is 0.5. The ratio during transport in high magnitude flow events is much higher. In Mt. Sdom, Dead Sea region, where the rocks and mantle exposed are commonly shales, sand and gravel, there is practically no fines in bed material sampled between floods while there is up to 50% of fines transported during floods (Gerson, 1977).

The materials winnowed during flow are deposted mainly in alluvial fan toes, where they may occasionally be mixed with some gravel. Bimodal distributions, then, are more typical to talus hillslopes and fan toes. Selective transportation is characteristic especially of environments where there is a

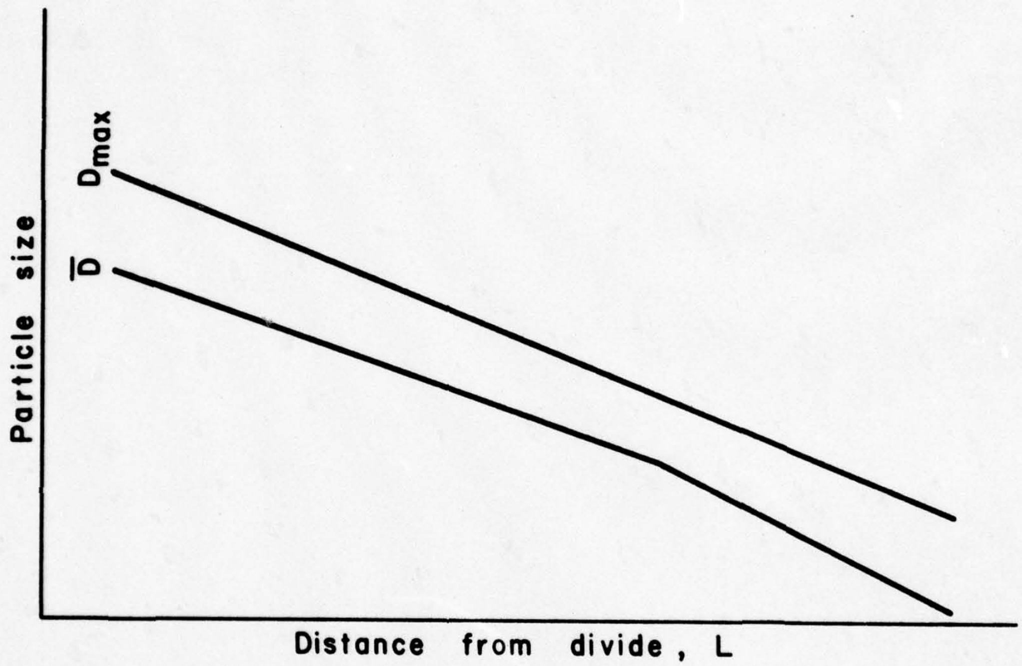


Figure 4:11 Trends of change of average and maximum particle size with distance from divide.

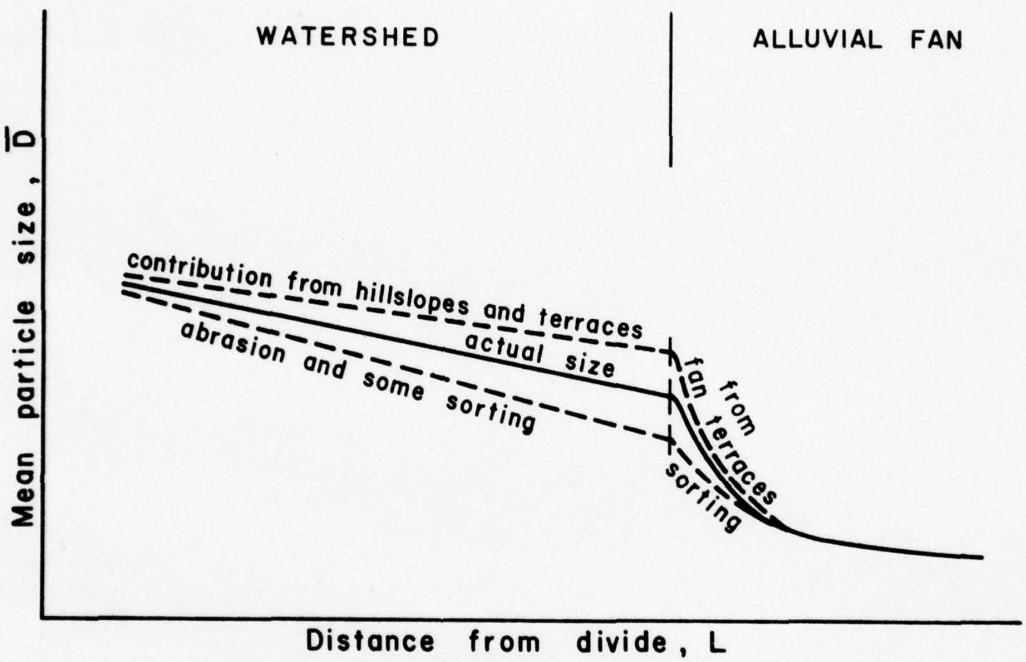


Figure 4:12 Trends of effects of abrasion and input from hillslopes and alluvial terraces on decrease of particle size downstream.

clear cut critical power distinction between bed load and suspended or wash load.

Contrary to abrasion and sorting, which lead to a decrease in size downstream (Figure 4:11), there is a factor which tends to increase size and is effective to some extent, but does not change the net trend. This factor is the addition of clastics from the hillslopes and sometimes alluvial terraces, which may contribute any available sizes to the already abraded and sorted sediments that pass the same point (Figure 4:12).

4.2.4.1 Rates of Abrasion and Decrease in Size

In non-aggrading gravelly streams, weathering during storage and the rate of abrasion during transport is equal to rate of decrease in size downstream. This rate is dependent primarily on the mechanical properties of the rocks composing the gravel, and the amount of work done by wear processes.

The variation of rock resistance to abrasion is very high. It depends mainly on differences in the hardness of the building minerals, rock texture, rock structure and rock weatherability

There are only a few studies dealing with resistance (relative resistance) of different rocks and their abrasion during transport. Of these, Plumley's (1948) and Carlson's (1974) studies are the most instructive. Carlson stresses that the general petrographic descriptions of many rocks, mainly igneous and metamorphic, cannot be applied as representing mechanical properties or definitions for use in assigning relative rates of mechanical abrasion.

Hence, between the most resistant, such as chert and quartzite, and the least resistant, such as sandstones, a whole gamut of rock types can be placed in various orders. Weathering during rest and temporary (rather long) storage in desert stream channels is probably an important factor in decrease in size, especially in the most weatherable rocks like coarse-grained quartz monzonite and sandstones.

Several factors affect the rate of decrease in particle size in the stream channel:

1. Contribution from hillslopes, which tends to diminish the rate of size decrease. This is espeically true in debris flow affected terrains.
2. Contribution from eroded alluvial terraces.
3. Rate of abrasion and weathering.
4. Selective transportation - sorting.

All these may interact in different fashions, which end up in some weighted resultant.

Because of the high degree of heterogeneity of processes in space and time in arid fluvial systems, the effect of one or more of these componenets may be decisive at any given point in space or time or, for some time (10^2 to 10^3 years), affect long reaches or the whole system

4.2.4.2 Sorting of Gravel in Arid Fluvial Systems

Sorting is the spread of particle size, its deviation around the mean. A sediment is well sorted if the spread is narrow and poorly sorted if the spread is wide. Sorting is usually poorer as particle size increases

(Inman, 1949). As sediment size decreases downstream, there is an increase in sorting in the same direction.

In gravelly streams which are graded, and where there is a long term balance between sediment supply and transport, selective transport is not effective because no continuous accumulation of the coarser fraction occurs They are not left behind. The same applies to degrading streams or stream reaches.

Gravelly stream channels in arid regions are a "combined" environment in terms of decrease of size and sorting of sediment downstream. Selective transportation affects mainly extreme sizes. Boulders contributed to valley bottoms by debris flows are left behind and clay to granule fractions are winnowed, carried selectively by most floods. Stream channels in arid regions represent, more than in any other environment, sediment transported and deposited by flow events of diverse magnitudes and unknown frequencies. They respond completely only to events of high magnitude. A stream channel's reach under observation is a sedimentologic end-product of various, superimposed, flood events of highly variable and unknown magnitude and frequency. Bed bottom configuration and sediment size characteristics are generally inherited from a lengthy past.

The results of this situation are clear. A low degree of correlation between size characteristics (such as mean size, maximum size, sorting, log-normality of distribution) and channel features (such as slope, distance from divide) exists in gravelly channels of arid regions. This trend is enhanced by en route contribution of sediments related to localized events on hillslopes and stream tributaries.

4.2.4.3 Change in Gravel Size in Fluvial Systems - Trends, Rates and Deviations

As stated above, there is a general decrease in gravel site downstream, affected by abrasion, weathering, sorting and input from older alluvial deposits. The former three factors enhance the rate of decrease, while the last may influence the rate either by decrease or increase.

The rate of decrease should be best correlated with dynamic variables, namely unit discharge or unit stream power, but it has not yet been studied for streams carrying gravel, whether perennial or ephemeral. The only relationships available are between particle size and some morphometric variables, such as drainage area, distance from divide and slope. These variables are essentially correlated with water discharge and stream power, but in a quantitatively inadequate fashion for ephemeral streams transporting gravel.

There are several studies relating particle size to morphometric variables, mainly distance from divide and channel slope (Sternberg, 1875; Shulits, 1936; Krumbein, 1937; Yatsu, 1955; Sundborg, 1956; Hack, 1957; Miller, 1958; Brush, 1961; Denny, 1965; Bluck, 1964; Rana, 1971; Bogardi, 1974). Only three of these are concerned with the arid (Bluck, 1964; Denny, 1965) and semiarid (Miller, 1958) environments, and only one (Miller's) with stream channels within the mountainous watersheds.

The results of these studies, relating particle size and rate of change to morphometric variable, are:

1. Particle size is correlated with distance from divide in an exponential or a power function:

$$D = D_o e^{-aL} \quad (\text{or } S = S_o e^{-kL})$$

$$D = aL^{-b} \qquad D = CS^f$$

Where: D = particle size; D_o = initial particle size.

a = abrasion or sorting coefficient; L = distance from divide.

S = channel slope; S_o = initial channel slope.

2. It cannot be predicted what sort of function, exponential or power, would better fit a given case.
3. For both perennial graded streams and flumes, transporting fine gravel and sand, it was noticed that:
   (a) There is a change in the rate of decrease in particle size where there is a change in flow regime.
   (b) There is a change in the rate of decrease in particle size where there is a change in bedform.
4. There is no universal relationship between a and k in the exponential equations.
5. In most cases, there is low regression coefficients for correlations between particle size and either distance or slope for gravels channels. Generally, the smaller the watershed, the lower tends to be the regression coefficient (see Brush, 1961).
6. In most studies it is implied, although not specifically stated, that distance from divide is some approximation of drainage area, to which discharge may be adequately related in humid terrains (Hack, 1959).

123

7. In two studies (Miller, 1958; Brush, 1961), relating particle size to distance from divide and from channel slope, the former bears a more significant relationship. This is so, contrary to the reasoning that channel slope and particle size should be dynamically related, the former being a determinant of stream power, and the later - a dependent on stream power.

Five watersheds were sampled for gravel along their water courses in the present study (see Appendix B):

1. A watershed in the Mohawk Mountains and its deposits in the San Cristobal Valley (southwestern Arizona).
2. Boulder Wash in the Gila Mountains (southwestern Arizona)

3 to 5. Three watersheds in Copper Mountains, Mojave Desert, southern California.

These watersheds appear to be typical of the hot desert terrains of the Basin and Range Province (see Section 2.2):

1. They drain relatively narrow mountain ranges into wide depositional basins.
2. Drainage area and stream length are relatively small, being several km^2 and km, respectively.
3. Available relief is 150 to 300 m.
4. Lithologic environments are characteristic of vast mountainous terrains of the Southwest, granites, diorites, gneisses, schists, amphibolites.
5. In the two first cases (in southwestern Arizona) there is a well-developed sequence of Quaternary-Holocene deposits.

6. Development of depositional basin depositional landforms appears to be mature and not interrupted by playas.

Three sedimentary attributes were tested against channel slope, distance from divide and drainage area. These are mean size, sorting (or standard deviation) and maximum size. Channel slope is a stream power related variable; distance from divide may reflect degree of abrasion; drainage area has a direct bearing upon discharge, power and selective transportation.

Univariate and multivariate analysis relating the three sedimentary characteristics to the three environmental variables (see Appendix H). These readily available variables seem to be the closest related to sedimentary characteristics, in view of the absence of data of dynamic nature.

Appendix H presents the analytical procedure used for correlating size characteristics (mean particle size, standard deviation and maximum particle size) with channel or fan slope and distance from divide. Drainage area was included at the beginning as an independent variable but was found the least important in explaining the variation and could not serve as a measurable variable once the stream channel entered the depositional basin:

Inspection of Tables H-7 through H-18 yields the following conclusions:

1. Particle size characteristics are better correlated with channel slope than with distance from divide.

2. There is no general situation of one sedimentary variable being better correlated with either slope or distance than others.
3. Mean particle size is better correlated in most cases with channel slope (r = .81-.99) than with distance from divide (r = -.30 - -.98). Better correlation to channel slope is because of the direct involvement of slope in tractive force/particle size relationships (see Section 4.2).
4. Maximum particle size is also better correlated with slope than with distance, for the same reason as mean particle size. Here, r is lower for both slope and distance, being .17-.98 and -.32 - -.98, respectively. Degrees of correlation are lower because larger particles may rest as lag deposits from high magnitude events and are not being transported while the channel slope is adjusted to more frequent flows.
5. Sorting, as well as mean and maximum particle sizes, is better correlated with slope than with distance. The reason is the same as for mean particle size. It has to be born in mind that the sorting here refers to the gravel fractions only and not to all sediments, including fines.
6. There is a difference in correlation of size to slope between small and large watersheds. In small watersheds such as Tall Tale, Bumble Bee and Lost Home (all in Copper Mountain, Mojave Desert) correlation of mean particle size with slope is better than correlation of maximum particle size with slope. This is not the case in larger watersheds, such as Boulder Wash or Stoval Mohawk in southwestern Arizona. The reason is the difference of competence; small watersheds yield less competent flows than larger ones.
7. Logarithmic treatment of the data yield similar coefficients of correlation, having similar significance.

8. In the multivariate analysis the program used slope as the first, better correlated, variable and then added distance from divide. In most cases there was some, not appreciable, improvement by adding the second variable. Attempts to use drainage area within the mountainous basins did not improve the multiple correlation. Here, as in the bivariate analysis, logarithmic treatment did not change the overall relationship.

There are several reasons for the relatively low coefficient correlations:

1. Most flow events are not effective (in both magnitude and duration) in adjusting sediment characteristics to flow variables.
2. Differential areal activity and partial contribution of runoff and sediment tend to scatter particle size distribution according to localized events.
3. Even in generally graded stream systems or channel reaches many flow events behave as in ungraded systems, transporting sediment in a selective fashion.
4. Any given alluvial channel reach represents, most of the time, sedimentary features created by various flow events. It is a sediment mixture deposited by superimposed events of unknown magnitude, frequency and number that is exposed along the channel at any given time.
5. Sampling of ephemeral stream sediments is conducted in most cases during no-flow periods. These are performed in pool-riffle and braided channel systems, in themselves very diversified in sedimentary characteristics.
6. Most arid stream channels in watersheds and alluvial fans are eroding older alluvial deposits along their banks and beds. These eroded

materials represent deposits adjusted to some degree to different flow regime combinations. Holocene debris flow remnants, including large boulders, are eroded and mixed with present-day sediments, as well as finer Q_2 gravel and sands, eroded from stream and fan banks.

7. Further scatter is caused locally by shifts of stream channel/ alluvial fan transitions as well as shifting flow within the braided flood plain with time and event.

Fluvial systems yielding the better correlations between size parameters and morphometric variables were Boulder Wash in the Gila Mountains and Mohawk-Stoval in the Mohawk Mountains - San Cristobal Valley.

For these two areas, sampling of Q_2 (late Quaternary - earliest Holocene) gravel along the alluvial piedmont, were sampled, analyzed for size characteristics and correlated with distance from divide and local piedmont slope.

Very poor correlations were obtained for these samples. Bivariate correlation coefficients for mean particle size and distance range between -.31 and -.40, while coefficients for mean size/slope relationship are -.005 - +.20. Multivariate analysis, using distance as first-step variable, yield correlation coefficient ranging between .60 and .80.

These low coefficients are related to several difficulties:

1. Sampling may be conducted only at a few sporadic fresh exposures;

2. One cannot attribute sampling sites to definite channels on sedimentary units within the fairly variable Q_{2i} sequence;
3. Degree of exposure of somewhat cemented particles is not complete;
4. Distance from divide cannot be measured in marginal areas that may be related to one of 2-3 adjacent watersheds;
5. Original surface slope is not measurable due to the changes the original clastics underwent since deposition: burial, desert pavement and soil formation, cementation.

Inadequacy of data and changes through time render such an anslysis of Q_2 sediments futile for tracing rates of change of particle size parameters.

4.3 DEPOSITION OF SEDIMENT IN STREAMS CHANNELS OF ARID REGIONS

4.3.1 GENERAL CONSIDERATIONS

Change in any of the variables involved in generally uninterrupted sediment transport may cause erosion or deposition. These would be discharge, total sediment load and sediment size, mainly through slope adjustment, and either degradation or aggradation can occur. Lengthy, permanent or other systematic change will lead to a general trend of change in the whole system. Following Lane (1955) and Gessler (1971), one may use the following equation:

$$Q_s \propto \frac{\bar{v}ds}{D}$$

Where: Q_s = sediment transport per time and unit of width

$\bar{v}$ = mean velocity

d = depth

s = slope

D = particle size

The main constraints that will lead to deposition are decrease of velocity, depth, discharge and slope and increase of grain size.

All these may change because of variation of flow characteristics with space, as is typical to arid fluvial systems (see Section 3.2) and with time, as is the case during the short term (difference between flow events within a period of months and years) or the long term (10^3 years), as most hot arid regions underwent during the late Quaternary and the Holocene (see Chapter 5).

130

One of the major and systematic changes that has occured in the depositional basin portion of the fluvial system is a continuous decrease of slope, irrespective of the other variables, as inevitable deposition proceeds. This is one of the causes for a possible general fining of material towards the top of the sedimentary section at the toes of alluvial fans and towards the center of the basin. Also, there is a decrease in stream power because of the abstraction of discharge into the permeable deposits. This would affect both depth and velocity of flow, especially in low to moderate magnitude flow events, and enhance deposition of sediment.

4.3.2 ALLUVIAL FANS

Alluvial fans are the characteristic landform of gravel deposition in the piedmont zones (Figure 4:13). An updated review of alluvial fans was recently published by Bull (1977). Here we will be concerned mainly with the points leading to prediction of particle size and their areal distribution.

There are several types of alluvial fans:

1. A single, non-segmented alluvial fan.
2. Segmented alluvial fans, with oldest fan apex near the mountain front (Bull, 1964).
3. Segmented with the youngest segment at the fan complex head, especially in tectonically active areas (Hooke, 1972).

Types 1 and 2 are the most frequent. Most studies were concerned mainly with type 1 and several generalizations emerged.

Figure 4:13 Old (non-active) and active alluvial fans at Surprise Canyon on the west side of Panamint Range, California. Present-day fan is considerably smaller relative to source area.

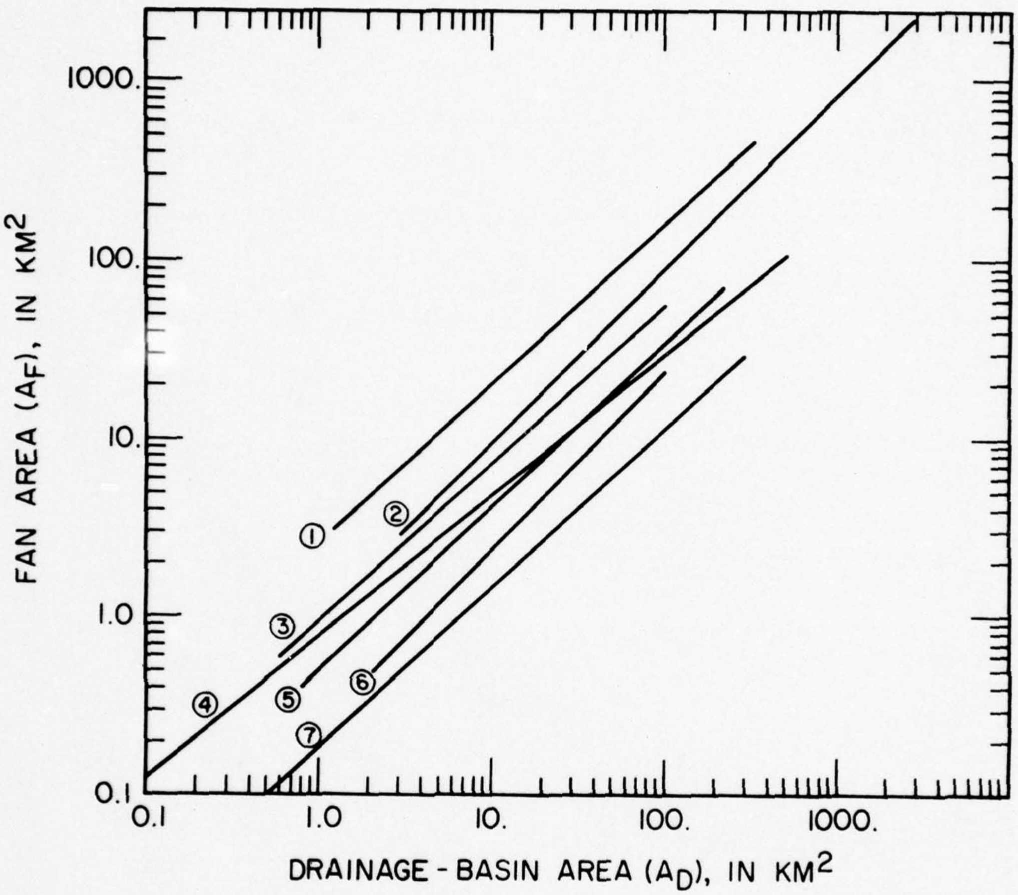


Figure 4:14 "Relations of fan area to drainage-basin area for groups of fans in California and Nevada. The equations and sources of data are as follows: (1,2) $A_f = 2.1A_d^{0.91}$, $A_f = 0.96_d^{0.98}$, least square revisions from Bull (1962); (3) $A_f = 0.74A_d^{0.98}$ (Hawley and Wilson, 1965); (4) $A_f = 0.5A_d^{0.8}$, depositional parts of fans (Denny, 1965); (5,6,7) $A_f = 0.42A_d^{0.94}$, $A_f = 0.24A_d^{1.01}$, $A_f = 0.15A_d^{0.90}$ (Hooke, 1968)" (from Bull, 1978).

Fan area is proportional to watershed drainage area (Figure 4:14), the relation being:

$$A_f = CA_d^n$$

Where A_f = fan area; A_d = watershed drainage area; n = an exponent, ranging between 0.8 and 1.0, usually around 0.9, and C = a coefficient.

While n does not vary systematically with detected environmental changes, "'C' appears to be constant for groups of fans in a given geographic, tectonic and climatic setting, but varies from one group of fans to another" (Hooke and Rohrer, 1977, p. 177).

The main difference in C is probably caused by lithology and structure. In Fresno County, California, watersheds draining more erodible materials, such as mudstone and shale, may produce fans twice as large as those produced by drainage basins underlain by sandstone (Bull, 1964). The same trend was found by Hooke (1972) in Death Valley, where watersheds underlain by dolomites and argillites produced larger fans than others. In all cases, erodibility is the key factor. In most cohesive rocks, erodibility is correlated to joint spacing because composing particles or mineral crystals or aggregates are practically undetachable in most unweathered igneous and metamorphic rocks.

A study by Hooke and Rohrer (1977) has clearly shown that the denser the jointing, the larger the fan in area and volume, pointing at a correlation between jointing and erodibility, which determines sediment yield (see Section 4.1.5).

A conclusion may stem from the foregoing. Particle size, partially dependent on joint spacing, has an inversely proportional relationship with sediment yield.

$$S_y \propto J_s^{-b}$$

$$D \propto S_y^{-d}$$

$$D \propto J_s^{c}$$

Where S_y = sediment yield, J_s = joint spacing, D = particle size, and b,c,d = positive exponents.

Inspection of Figure 4:15 yields a possible inverse relationship between particle size and sediment yield within the mountainous watershed. This relationship is not necessarily causal in nature. There may be several reasons for this phenomenon:

1. Selective transportation increases in effect downstream, with increasing stream power. This increase in selective transportation is not high enough to obscure/hide the general trend of abrasion as a major size-decrease mechanism.
2. The dominance of selective transportation manifests itself on the alluvial fan where deposition is a major trend.

Our knowledge of sediment yield from arid watersheds is too poor to speculate quantitatively about the relationship.

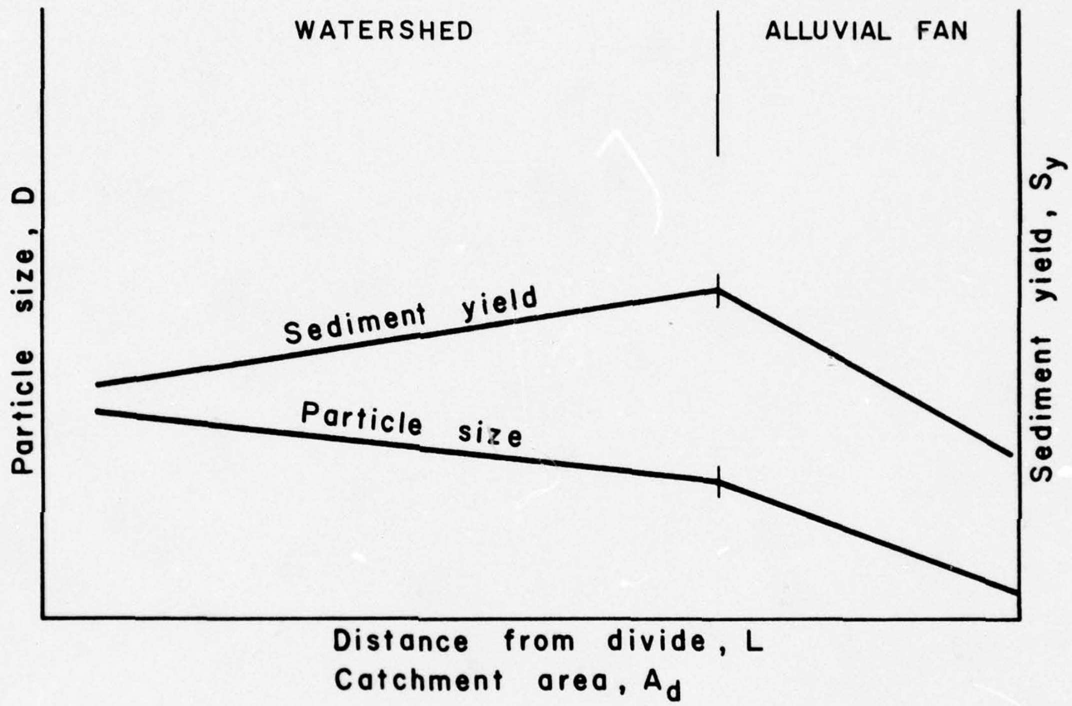


Figure 4:15 Changes in gravel particle size and sediment yield with distance from divide.

Fan slope appears to be related to erodibility of bedrock, particle size and size of source area. Although no multivariate analysis has been performed, there are some observations on these relationships.

1. Steeper fans are derived from source areas with high rates of sediment production (Bull, 1964).
2. Steeper fans are sometimes associated with smaller watersheds (Hooke and Rohrer, 1977). Yet, hydraulic variables are not the only ones taking active role in determining the size of a fan. Tectonic activity, or creation of a given fall between the top and the base of a piedmont, will effect the size and shape of an alluvial fan, being traversed by existing streams, small or large, in catchment area. Therefore, some piedmonts are gentle or steep, largely as the result of total available relief.

These observations show that both capacity and competency of a stream is related, among other variables, to slope. When the amount of sediment relative to the power of the stream is greater, the slope of the stream is steeper. When the particle size is larger, the tractive force necessary for its transport is higher. When the catchment is smaller, the discharge is smaller and, hence, the slope for carrying available sediment is steeper, both in quantity and size. Both Blissenback (1952, 1954) and Bluck (1964) confirmed a close relationship between the rate of change in slope of the surface of an alluvial fan and the rate of change in its maximum particle size.

Fan toe boundaries change because of various reasons.

1. Climatic change, resulting in change of stream discharge, particle size and sediment yield. Change of climate to a wetter mode usually will tend to expand alluvial fans.
2. Tectonic activity, uplift of a mountain range would lead to increase of both discharge and sediment yield; entrenchment, segmentation and expansion of alluvial fan complex.
3. Attainment of maturity of a fan, without any climatic or tectonic change may lead to segmentation and expansion of a fan complex, or following a decrease of slope due to continued deposition in the depositional basin, a decrease of expansion and even decrease in size.

For practical prediction purposes in this report we will consider two possibilities:

1. A steady rate in fan growth, both in thickness and in area (Hooke, 1968). This case may apply to areas where fans are not segmented and bound in their toes by active deposition of playa or eolian materials. The result is similarity in area and particle distributions through time; especially considering the upper 10 to 30 m of the alluvial section. Alluvial fans may respond to morphometric changes in the source area with time, or to climatic changes. Both have occurred in the southwest United States, the former as a result of denudation and the latter in the middle through late Quaternary and Holocene.
2. Evolution of alluvial fans as the depositional basin is filled with time, with no tectonic activity affecting the process. With time, the piedmont zone of the depositional basin becomes gentler in gradient as deposition proceeds. Decrease of slope results in decrease of power and areal expansion of gravel deposition ceases. Fans may shrink in

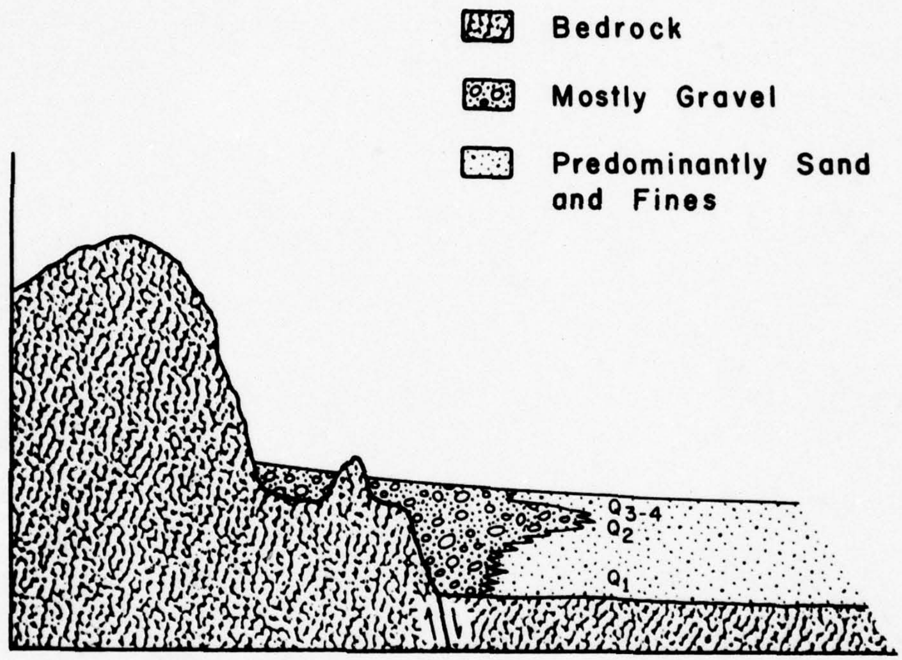


Figure 4:16 Schematic section through a depositional basin, with interfingering contact of gravel to finer sediments.

size to a steady state area where deposition near the moutain front, both on the fan and in the valley, governs slope and boundaries.

A general model of gravel deposition emerges, considering climate change in an actively filling depositional basin (see Chapter 5, with respect to types of fill characteristics to southwestern United States during the Quaternary and the Holocene). This model (Figure 4:16) takes into consideration two factors:

1. With no active mountain uplift, the depositional basin is being filled with time and its gradient decreases accordingly. This results in decrease in available power and fining of sediment in the upper parts of the alluvial section until a dynamic equilibrium is reached, at which point the size of a given fan is determined and the boundary of gravel and coarse sand deposition remains almost fixed.
2. Climatic perturbation would determine both the amount of sediment and its size characteristics. In wetter modes of operation, yield and size may be smaller due to increase of terrain protection by vegetation and a higher degree of chemical weathering. This would result in fining of transported sediment.

Figure 4:17 is a schematic sketch of the possible trends of mean particle size or maximum particle size with distance from divide; the general trend of both parameters is similar. It is reasonable to assume that there would occur a sharp drop of size as the stream enters the more braided and ungraded alluvial fan zone. The higher rate of change may appear either abruptly at the apex of the fan (1) or assume a gradual form being higher at the lower fan (2). In many cases, because of the effect of medium to high magnitude

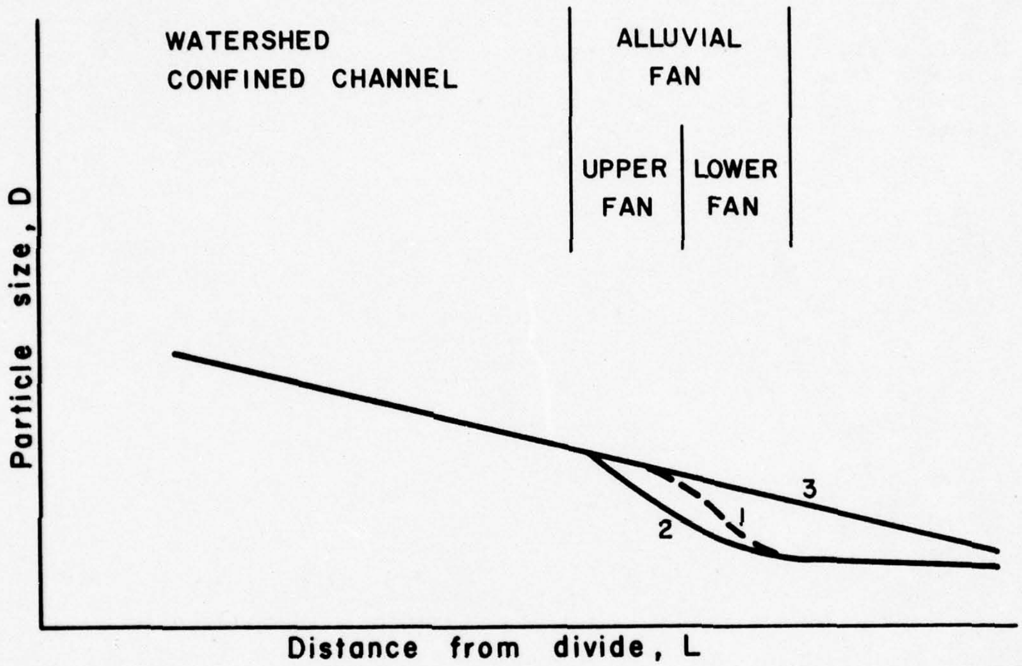


Figure 4:17 Change of particle size in alluvial fan zone - three possible trends.

flow events, there is no actual change in rate of decrease (3), as the results in section 4.2.4.3 show.

In most piedmonts mantled continuously by alluvial fans, fan arcs range between 60° and 120°. Having empirically determined the c and n in the equation $A_f = CA_d^n$ for a given piedmont, the distance to which gravel may be anticipated in an unsegmented alluvial fan terrain can be simply predicted by the equation

$$L = \frac{2CA_d^n}{\alpha}$$

Where L = fan radius or length from apex

α = fan arc, in radians

for $\alpha = 60^\circ = 1.05$ radians $\quad L = \dfrac{2CA_d^n}{1.05}$

and for $\alpha = 120^\circ = 2.10$ radians

$$L = \frac{2CA_d^n}{2.10}$$

4.4 THE EFFECTS OF HIGH MAGNITUDE EVENTS (EXTREME, "CATASTROPHIC" EVENTS)

The frequency of high magnitude events, occurrences of debris flows on talus slopes or extreme flows in channels, is not yet known in deserts. There are not enough data or observations of the intense events in the arid regions for even a fruitful postulation of space-time transformations (Wolman and Gerson, 1978).

Nevertheless, observations both on hillslopes and in stream channels in arid regions yield a few general conclusions.

1. It is mainly debris flows that deliver most of the larger fractions, large cobbles and boulders, to stream channels, even in fluvial systems in tectonically non-active terrains.
2. Most extreme rainfall events in deserts are localized. They encompass areas of 10 to 25 km^2 (see Section 3.2).
3. It is quite rare that more than a few debris-flows will occur in a small watershed at the same event.
4. Localization and high coarse-debris concentration may lead to deposition along the valley bottom and on fans close to the mountain fronts. There is a very poor chance of large boulders being transported more than several hundred meters from the mountain front.
5. Boundary events, which are high enough in rainfall intensity but still do not cause extensive debris flows, move boulders sporadically down stream or down-fan. This is why one does not frequently encounter debris flow imported boulder concentrations in stream channels, at the floor of debris flows remnants on the hillslopes and on alluvial terraces.
6. Fan-head entrenchment and evolution of segmented alluvial fans, in many cases in a telescopic fashion, is sometimes attributed to extreme events (Beaty, 1970).
7. Competence of extreme flow events is high, mainly because the $\bar{d}$ x s product is especially high during the later part of the rising limb of a hydrography. Loss of competence is detected downstream from the apex of alluvial fans where water distribution among several braided channels and transmission loss combine to reduce both $\bar{d}$ and s. Hence, it is unlikely to find large cobbles and boulders more than half way down-fan.

Examples of the effects of extreme events in arid zones are many, but very few have been studied. One is found around Sheep Mountain, in the Gila Mountains,

Figure 4:18   Remnants of Holocene debris flows, Sheep Mountain, southwestern Arizona.

southwestern Arizona (Figure 4:18). In a primarily granitic terrain, there occurred in the early Holocene an event that produced debris flows transporting large quantities of up to 2.5 m sized boulders. Small watersheds, having catchment areas of $\leq$ 4.0 km^2, were affected by the event that centered around Sheep Mountain. Most of the coarse gravel came to rest on valley bottoms and small alluvial fans. The high magnitude activity took place within a diameter of 7.0 km. This extreme boulder transporting event occurred only once because of the following possible reasons:

1. No occurrence of such an event from the late Quaternary to the present.
2. Depletion of such large-sized materials by the single event. The fact that we do not have evidence of another such event may depend on the availability of large-sized materials, and does not exclude the possibility that such a climatic event did occur after the one described here.
3. Change of climate-process conditions. Major debris flows may have occurred during the transition from the wetter, later Quaternary to the drier Holocene. At the transition period there still existed a mantle of soil-covered talus, providing the quality and amounts of matrix materials necessary to operate major debris flows.

The matrix has been washed and the boulders have been darkly varnished since the early Holocene. Today only coarse gravel to very large boulders constitute the remnants (see Section 4.1.3).

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5. CHARACTERISTICS AND IDENTIFICATION OF QUATERNARY FLUVIAL DEPOSITS
by Louis H. Fleischhauer

5.0 FORWARD

The scheme of subdivision, criteria for recognition, and significance of Quaternary alluvial deposits in arid parts of California and Arizona were developed by W. B. Bull in previous unpublished studies, and are presented in detail in a book manuscript in preparation. References to study sites near Vidal, the Whipple Mountains, and the Riverside Mountains in California are mostly from his work. Data presented from the Sheep Mountain area, Yuma Co., Arizona, are from Bull (in preparation), Schenker (1977), and this study. Mohawk Mountains, San Cristobal Valley, and Aguila Mountains study sites, all in Yuma Co., Arizona, were investigated in this project.

5.1 INTRODUCTION

A suite of constructional piedmont surfaces can be identified and correlated across large areas of arid southwestern Arizona and southeastern California. These comprise mappable units and are designated from oldest to youngest as Q1, Q2, Q3, and Q4 (Bull, in preparation; Schenker, 1977). Several of the units can be subdivided into members which are designated by letters, e.g., Q2a (oldest), Q2b, and Q2c (youngest). All are Quaternary in age, although Q1 may be Pliocene in part. Q3 and Q4 are Holocene.

The criteria for distinguishing Q-units include surface morphology, sedimentology, and degree of soil development. At the highest level of categorization, these criteria can be given approximately equal weight in distinguishing Q-units. Subdivision of Q-units into members, however, emphasizes surficial morphology, such as degree of development and preservation of desert varnish and pavement, and soil features, such as the degree of B horizon development, and amount and morphology of calcium carbonate.

Although Q2 alluvium may be distinguished from the Q1 and Q3 units on the basis of sedimentologic properties, Q2a alluvium may not be readily distinguished from Q2b and Q2c on this basis. The same is true when comparing the alluvial fills of Q3 members surfaces. Because surface characteristics are easily discerned on air photos, these features are given highest ranking. Accordingly, the map units are considered morphostratigraphic units (Frye and Willman, 1962; Hawley, 1975). Fill units underlying the surface are referred to as Q2 alluvium or Q2 sediments, and soils formed on the surface are similarly designated.

5.2 Q1

5.2.1 SURFACE FEATURES

Q1 is the oldest and least preserved geomorphic surface. It typically occurs as highly dissected ridge and ravine topography as in the Gila Mountains of southwest Arizona (Fig. 5:1). However, near the Mopah Range in the Vidal area, California, it is preserved as a moderately dissected piedmont. Relief along ridge crests can range up to 13 m (40 ft) and relief between ridge crest and stream channel can range up to 30 m (100 ft). Pavements on Q1 are sparse and poorly developed, but boulders may show very dark varnish. Often only the most resistant lithologies persist as surface gravel.

5.2.2 Q1 SEDIMENTS

Sediments underlying Q1 surface remnants consist of poorly sorted, cobble-boulder gravel in a sandy matrix and are usually completely cemented by calcium carbonate. The thickness in the Vidal region, California, is on the order of at least 15 m (50 ft). The thickness and distribution of Q1 at Sheep Mountain (Gila Mtns., AZ) is irregular. Based on topography, 40-70 m (130-230 ft) is a minimum thickness. In places younger surfaces

are inset below high Q1 ridges, but elsewhere in the area, local remnants of Q1 sediments are buried by thin deposits of Q2 and Q3. Thus Q1 sediments can form a local, irregularly distributed alluvial basement.

5.2.3 Q1 SOILS

Soils are not well preserved on Q1 surfaces due to the extreme dissection. B horizons are not preserved in either the Vidal region or in the Yuma region. The only preserved horizons are calcic or petrocalcic horizons. Soils are classified as Paleorthids.

5.3 Q2

5.3.1 SURFACE FEATURES OF Q2

Q2 surfaces are smooth, flat, and moderately dissected with well-developed, highly varnished desert pavements (Fig. 5:1). Gravel comprising the pavements is fine-grained and well-sorted in comparison with Q1 and Q3 pavements. Mean size is around 16 mm, though particles may range up to 300 mm (Bull, book manuscript in preparation). The pavement gravels are closely packed with little bare ground between clasts, and are varnished to a dark brown, almost black color. Drainage networks arising within Q2 are dendritic and incised below the level of the pavement. No remnants of the former stream channels that deposited Q2 sediments are preserved on the surface.

Exceptions to the high degree of pavement development occur in areas dominated by medium- to course-grained granitic rocks. Granite weathers to granules and sand under almost any climate and, therefore, does not yield sufficient gravel to form the type of pavements found in metamorphic, volcanic or hard carbonate terrains. Instead, the surface can be mantled by a litter of feldspar phenocrysts and quartz and, since neither acquires

Figure 5:1   Aerial photograph of the Sheep Mountain area, east side of the Gila Mountains, Yuma Co., Arizona. The photo shows the typical expression of Quaternary geomorphic surfaces in arid southwestern Arizona and southeastern California. Q1 has light tone and forms ridge and ravine topography. Q2 has a dark tone and forms smooth desert pavements. Q3 is intermediate in tone with braided or plumose texture and has bar and swale topography. Q4 has light tone and consists of active channels and unvarnished pavement areas.

desert varnish, the surface remains light-colored or white. In such areas, the distinction between Q2 and Q3 surfaces from black and white air photos may be difficult and must be made in the field on the basis of soil development. Q2 surfaces may be redder as a result of soil color so that color air photos are useful. Examples occur in the southern Gila and Tinajas Altas Mountains of Arizona, and Coxcomb Mountains of California.

5.3.2 Q2 SEDIMENTS

Q2 surfaces are formed on sand, gravelly sand, or gravel that is inset against, or overlies, older rocks or alluvial fill. A salient characteristics of Q2 sediments is the fineness of gravel in comparison to Q3 or Q1 alluviums (Figs. 5:2 and 5:3). The matrix frequently has a reddish tinge, especially near surface. Gravel may range up to 300 mm in diameter, but these are rare. In localities with granitic source areas, Q2 alluvium is a reddish arkosic sand with only occasional, fine gravel.

5.3.3 Q2 SOILS

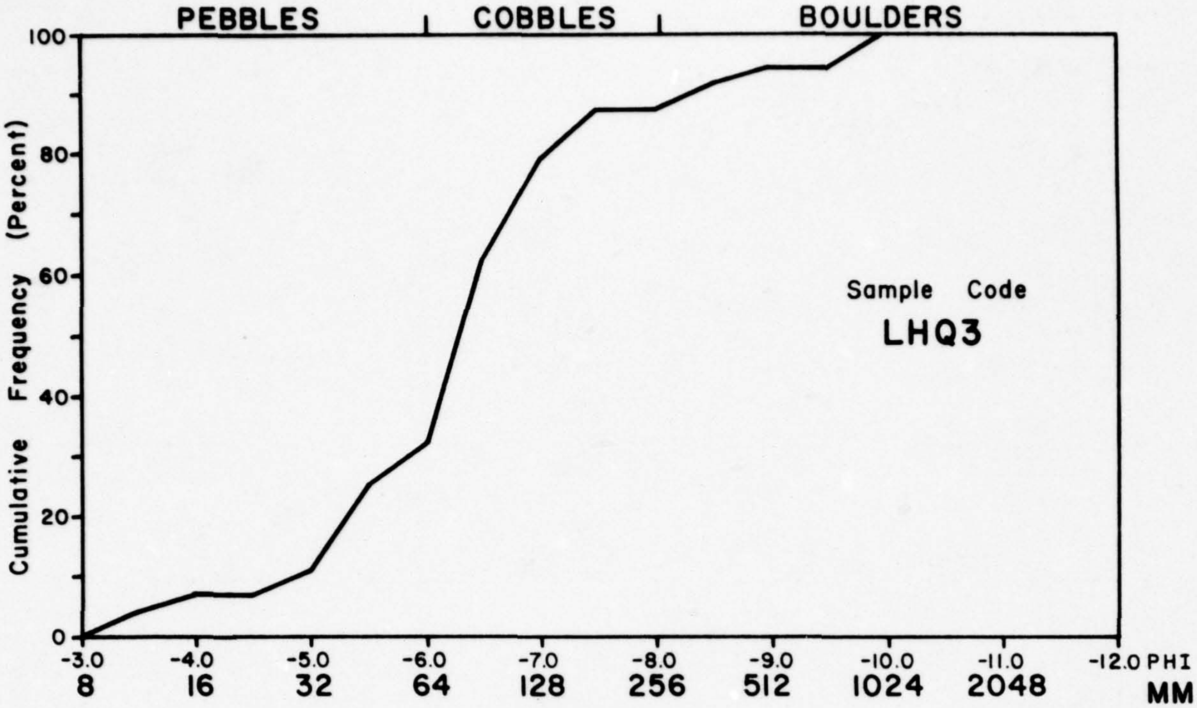
Soils of Q2 surfaces are characterized by development and preservation of B horizons. A generalized profile may take the form of:

A_v - vesicular A horizon, 8 cm thick.

B - cambic or argillic B horizon, 10 cm to 1 M thick.

Cca - parent material, with calcic horizon in oldest Q2 surface; carbonate occurring as pebble coatings, soft nodules, and some interpebble fillings.

B horizons have red hues of 7.5 YR to 5 YR. Clay content varies regionally, possibly as a function of climate. Near the Whipple Mountains, California (mean annual precipitation 95 mm), B horizons in even the youngest Q2



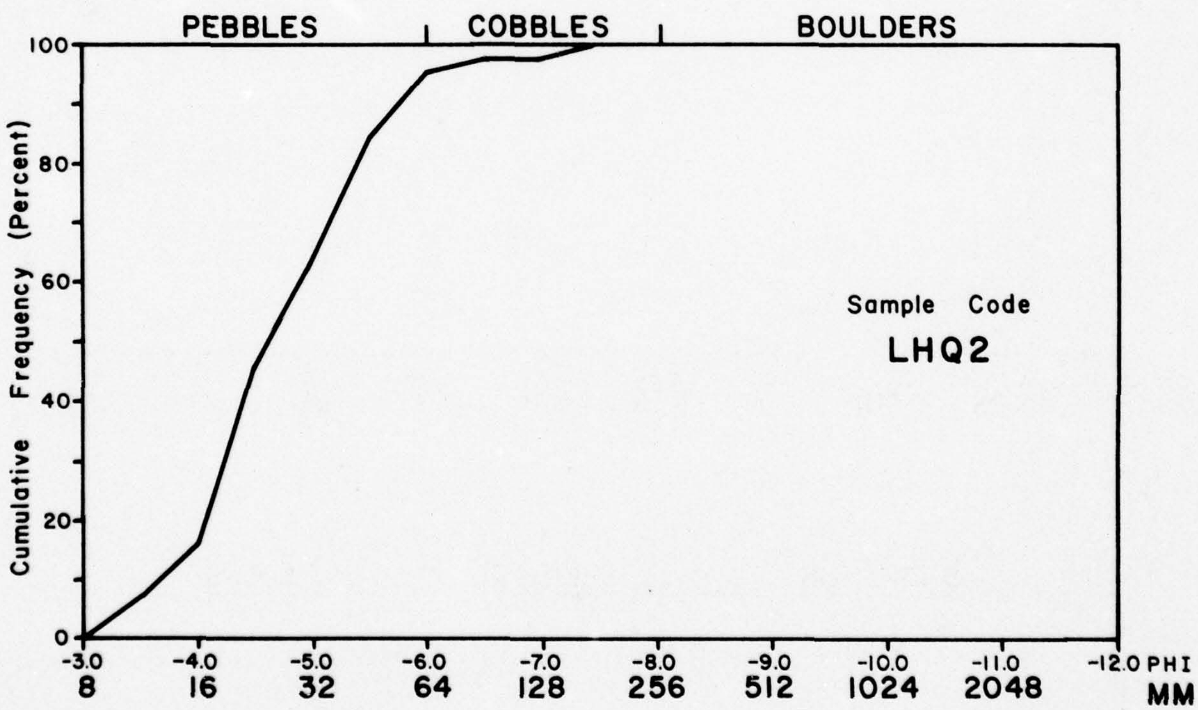


Figure 5:2 Cumulative frequency distribution curves for Q3 (LHQ3) and Q2 (LHQ2) sediments, exposed in a stream cut in the Lost Home Canyon locality, Copper Mountains, near 29 Palms, California. Note that Q3 is coarser and more poorly sorted than Q2. Figure 5:3 shows this locality.

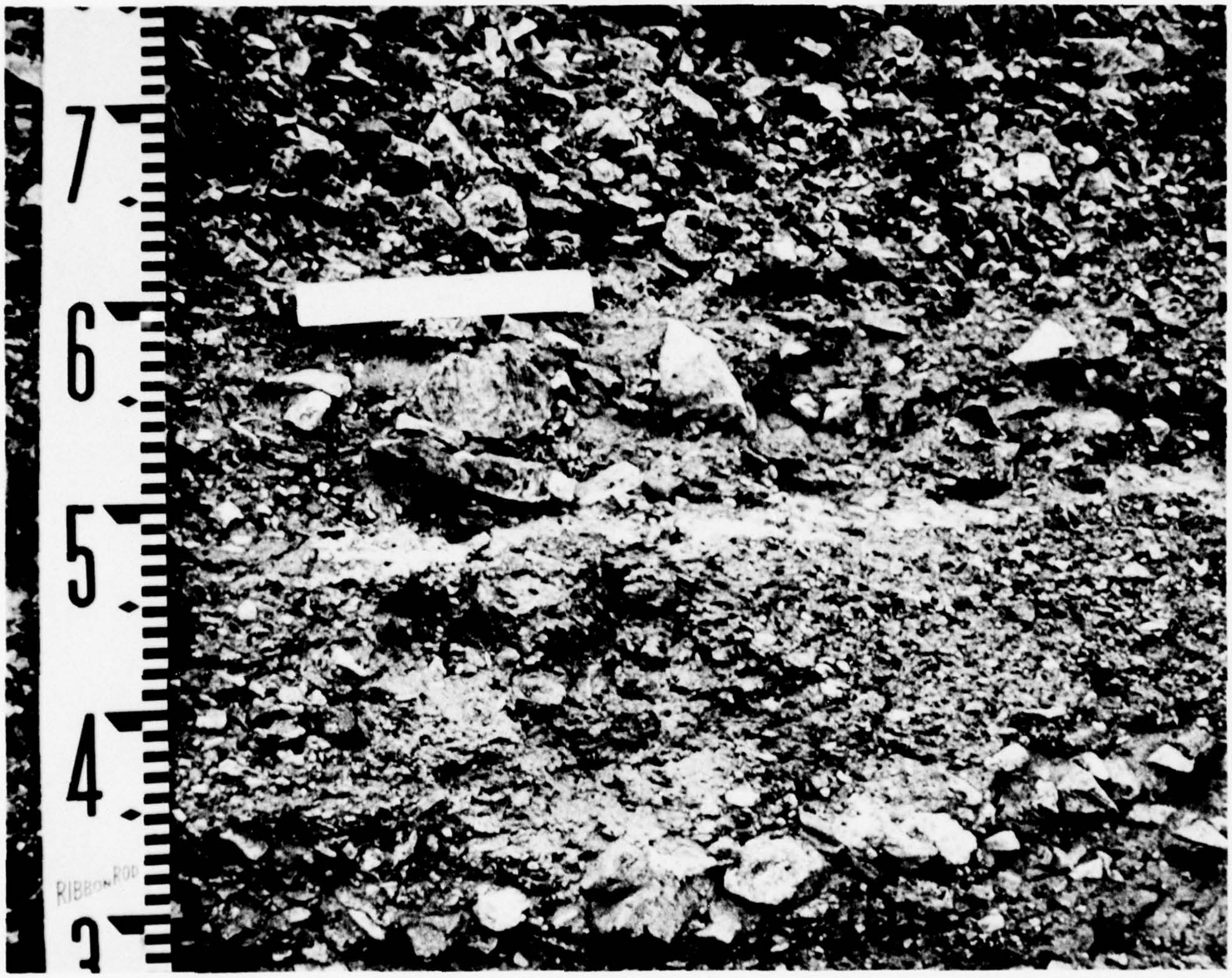


Figure 5:3 Q3 sediments overlying Q2 sediments in the Lost Home Canyon. The contact is at the small rule. The Q2 sediments have a higher proportion of fine-grained material than the Q3.

Figure 5:4 Photograph of Q2 soil near Sheep Mountain, Yuma Co., Arizona. The reddish brown B horizon (5 YR hue) is typical of Q2 soils.

surfaces are clay-rich and are usually argillic. Near Yuma, Arizona (mean precipitation 75 mm), B horizons are marked by reddish color and high silt content, but little clay. These are mostly cambic (Fig. 5;4).

Calcium carbonate occurs throughout the profile. Mesoscopic carbonate in the C and lower B horizons takes the form of thin discontinuous to continuous coatings on pebbles; soft, white nodules or interpebble fillings; or thin filaments. The amount of carbonate and the thickness of the zone of principal accumulation generally increase with age of the surfaces. Microscopic accumulations of calcium carbonate in the A and upper B horizons probably have been implaced during the Holocene and post-date the period of major development.

Q2 soils often have accumulations of chloride salts or gypsum depending on local climate, soil texture, and landscape setting. Gypsum occurs as small crystals a few millimeters in diameter. It is intimately associated with carbonate and clay in the profiles and forms discrete horizons with transitional tops and bottoms. The amount of gypsum and thickness of the horizon is probably sufficient to qualify some as gypsic horizons (Soil Survey Staff, 1975). These are hard or very hard when dry but none are petrogypsic. Holocene eolian additions and fluctuating, perched ground-water tables cannot be discounted as agents of introducing gypsum after the development of the principal soil properties. However, the position of horizons of gypsum accumulation beneath horizons of maximum clay accumulation and their association with calcium carbonate tends to confirm a pedogenic origin and suggests a cogenetic relationship with other soil properties.

In the San Cristobal Valley, Arizona, buried Q2 soils with pedogenic gypsum occur in non-gravelly material on piedmont toeslopes and valley centers. Higher on the piedmont, where parent materials are coarser and more permeable, gypsum generally does not occur within the upper meter or two of the profile.

Chlorides, probably as halite, occur in surface horizons of Q2 soils in the San Cristobal Valley, Arizona, and Whipple Mountains, California. The accumulations are generally microscopic but are readily apparent to the taste. Chloride ions are more mobile in soils than carbonate or sulfate ions and, as a result, generally occur at greater depths in the profile than either of these. The occurrence of chloride in surface horizons of Q2 soils indicates that they are a recent addition, post-dating the period of principal soil formation. Their effect is important in contributing to the physical breakdown of gravel through salt-splitting. Q2 soils in the San Cristobal Valley, Arizona, with appreciable chloride content frequently contain "rotten" pebbles that have been reduced to powder by this process. Large accumulations of mesoscopic chloride sals in sub-surface horizons have been observed only at Cipriano Pass between the Gila and Tinajas Altas Mountains, Arizona. Here, large crystals of halite associated with calcium carbonate act to cement the soil material into a hard mass. This type of accumulation does not appear to be widespread.

5.3.4 MEMBER SURFACES

Differentiation of Q2 into member surfaces is based on relative age as deduced from surface height, soil development, and degree of development and preservation of varnished pavement. The following are characteristics

exhibited in the Whipple Mountains, California, where Q2 surfaces occur as a sequence of terraces.

Q2a - The oldest Q2 surface. Pavement is somewhat degraded and the surface is the most highly dissected Q2 surface. The soil may be eroded to the Cca horizon, though where preserved, the argillic B horizon ranges from 50-100 cm thick. Calcic horizons can be plugged.

Q2b - Intermediate Q2 surface. Pavement is well-sorted and highly varnished. Soil is usually well-preserved. Argillic and cambic B horizons range up to 50 cm thick and average 23 cm. Calcium carbonate occurs as soft nodules and partial interpebble fillings.

Q2c - The youngest Q2 surface. Pavement is well-sorted and highly varnished. Cambic and argillic B horizons average 13 cm thick. Calcium carbonate occurs as soft, earthy nodules, coatings on pebbles, or filaments.

Soils of Q2 member surfaces near Sheep Mountain, Arizona also exhibit increased development with age except that clay accumulation in B horizons is not as pronounced due to a more arid climate. Q2a surfaces in that area are more eroded so that generally only Cca horizons are preserved (Schenker, 1977).

5.4 Q3

5.4.1 SURFACE FEATURES OF Q3

Q3 surfaces generally lack smooth, fine-grained pavements. Instead, these surfaces preserve the depositional features of braided streams, namely elongate, coarse-grained gravel bars and fine-grained, intervening low areas or swales (Fig. 5;1). On air photos, the bar and swale topography imparts a braided or plumose texture that is highlighted by

the differences in tone of the bars and swales. In most areas, this suite of surfaces is easily distinguished from the smooth, evenly toned pavements of Q2, but difficulties can arise with Q2a.

Q3 is developed as terraces inset against older alluvium or as mountain-front fans prograding over older surfaces. The duration of inactivity of these surfaces has been of sufficient length to allow the development of some varnish. With increasing age, the darkness of varnish and intensity of weathering of surficial gravel increases and the bar and swale topography becomes more subdued. On the youngest Q3 surfaces, andesite cobbles may still preserve the abrasion surface of stream transport. Granite and gneiss begin to weather rapidly and do not maintain the original shape of the clast. Where partly buried, miniature pediments have been cut at ground level on exposed parts of granitic boulders. Q3a surfaces will have varnish as dark as that of Q2 and the original relief between the bars and swales is greatly reduced.

The degree of reduction of relief between bars and swales is partly dependent upon the lithology and original texture. Where coarse-grained and composed of lithologies resistant to weathering, these bars will persist, but where they are fine-grained or composed of non-resistant lithologies, the relief is quickly reduced. On piedmonts of the Mohawk and Aguila Mountains, Arizona, the Q3a surface has a smooth, tightly packed pavement with dark varnish and is virtually indistinguishable on photos from Q2 surfaces. On the ground, however, vague remnants of bars having heights of 10-20 cm, or forming narrow belts of coarser pavement, can be identified. The Q3a and Q2 surfaces are readily distinguished on the basis of soils. In the same area, younger Q3 surfaces have

bouldery bars with 1 m of relief. Schenker (1977) notes that in the Sheep Mountain area, the oldest Q3 surface appears transitional to Q2.

5.4.2 Q3 SEDIMENTS

Fill units on which Q3 surfaces are developed vary in thickness. At Sheep Mountain, Arizona, they seldom exceed 2 m in downstream reaches, but exceed 5 m near mountain fronts. In the Whipple Mountains, California, Q3 terrace deposits exceed 8 m in thickness. Q3 fills of up to 33 m thick have been measured in the Riverside Mountains, California.

Lithologically, Q3 sediments consist of grayish, sandy cobble-boulder gravel or gravelly sand. The gravel fraction has larger maximum sizes and is more poorly sorted than Q2 gravel (Fig. 5:2). This textural difference provides an obvious contrast in sections where Q2 sediments are buried by Q3 sediments, especially if the former has a reddish tinge (Fig. 5:3).

5.4.3 Q3 SOILS

Soils developed on Q3 surfaces display A-Cca profiles. B horizons are not developed and colors are grayish with 10 YR and 7.5 YR hues. A horizons are 8 cm thick and vesicular. C horizons usually preserve original stratification. Q3 soils are calcareous throughout, and visible carbonate is restricted to thin, discontinuous coatings on pebbles.

5.4.4 MEMBER SURFACES

Member surfaces of Q3 are differentiated on the basis of relative height above modern stream channels, degree of varnishing, and degree of reduction of relief on bar and swale topography.

Q3a - Oldest Q3 surface. Varnish is dark and the general appearance of the surface is transitional with Q2. Bar and swale topography is reduced. Calcium carbonate in soils occurs as continuous coatings.

Q3b - Intermediate Q3 surface. Varnish is somewhat lighter than Q3a and the bar and swale topography is distinct. Calcium carbonate occurs as discontinuous coatings on pebbles in soil.

Q3c - Youngest Q3 surface. Varnish is moderate and bar and swale topography is well-preserved. Calcium carbonate occurs as discontinuous coatings on pebbles.

5.5 Q4

Q4 consists of active stream channels and depositional areas of piedmonts. Like Q3 surfaces, it has a braided texture, but unlike older surfaces, it has no varnish and lacks pavement development. Sedimentologically, it resembles Q3. Soil development is minimal with only A and C horizons. Although usually calcareous, the soils lack visible calcium carbonate coatings on skeletal grains.

5.6 AGE AND SIGNIFICANCE OF Q-UNITS

5.6.1 *FRAMEWORK OF CORRELATION*

Figure 5:5 is a time-calibrated stratigraphic section showing the glacial, alluvial, and lacustral sequences in southeastern California and the eastern Sierra Nevada, and the "state of the art" correlations. Columns A, B, and C are absolute time, geologic time, and magnetic polarity epochs, respectively. The latter is included to suggest which intervals have the greatest potential for age refinement using this method. Columns D and E present glacial and lacustral chronologies for California and provide a climatic backdrop for

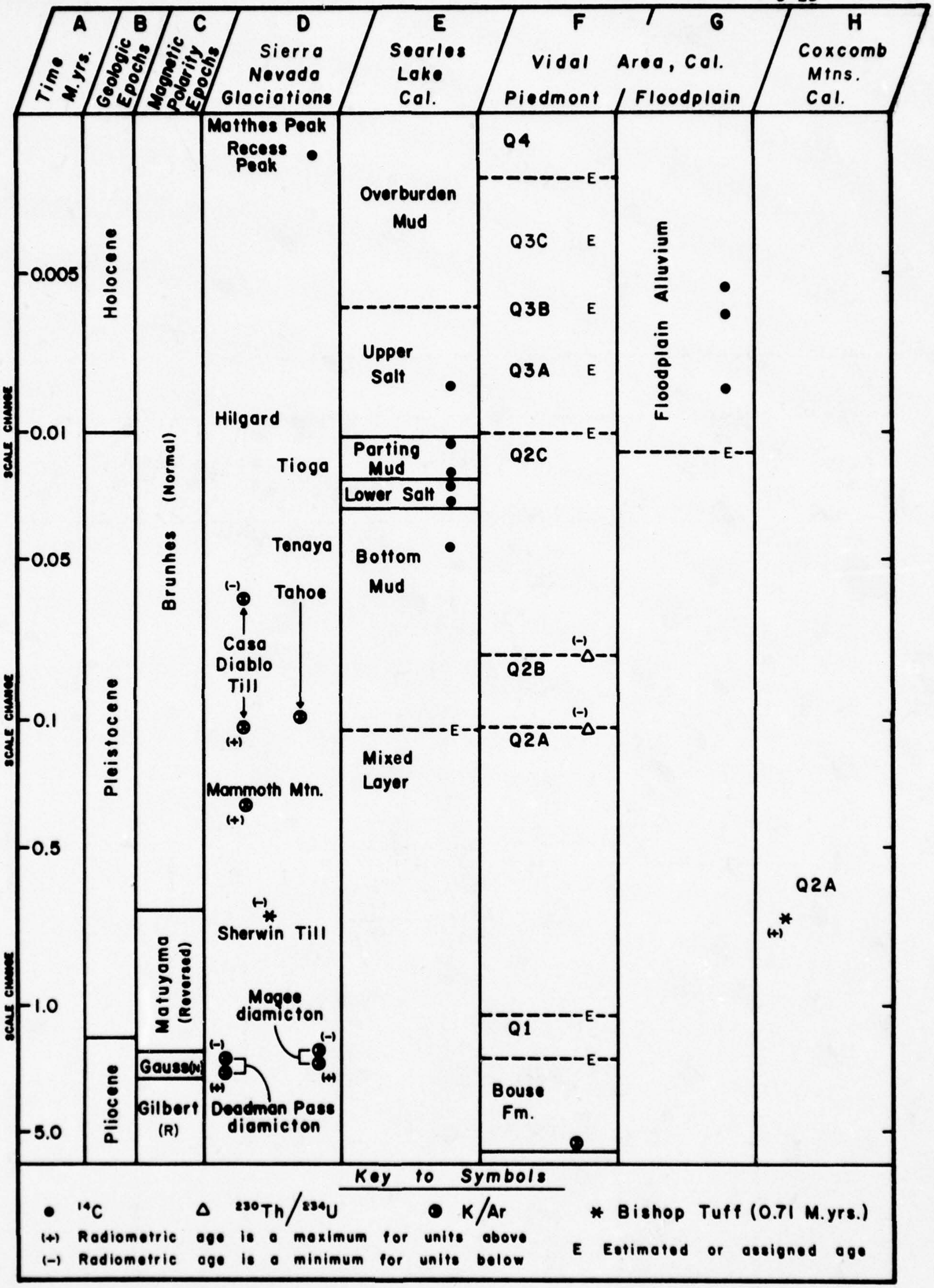


Figure 5:5 Time-controlled stratigraphic column of glacial, lacustrine, and alluvial sediments in arid southwestern Arizona and southeastern California, and the eastern Sierra Nevada.

the alluvial sequence. Sierra Nevada glacial tills are rather poorly dated and at best have bracketing dates (Birkeland and others, 1976; Porter and Denton, 1967). The glacial origin of the Deadman Pass Till and the Magee Till is questionable. The Searles Lake chronology is glutted with ^{14}C dates on both organic carbon and calcium carbonate (Flint and Gale, 1968; Stuiver, 1964; Smith, 1962, 1968). Recent ^{230}Th ages of Peng and others (1978) show a good correlation with ^{14}C ages and indicate the potential for extending this chronology. The overburden mud has ^{14}C dates but most of these show reversal of age trends. Columns F and H show the tentative chronology for the Q-units in the Vidal areas and are based on absolute and relative dating (Metzger and others, 1973; Ku and others, in preparation; Bull, in preparation.) Much of the discussion that follows will center on Column F.

5.6.2 AGES OF Q-UNITS

The age of Q1 has not been established by absolute dating techniques. In the Vidal area, it unconformably overlies the Pliocene Bouse Formation, which is a marine, estaurine, or perhaps delatic unit. Although the Bouse sediments may have been delivered by the ancestral Colorado River, they apparently pre-date the establishment of a through-flowing axial stream in this area. An ash associated with the basal limestone of the Bouse has been dated at 5.47 ± 0.2 m.y. (Damon and others, 1978). The minimum age of the Bouse is estimated on the basis of the age of the Colorado River in this region. An age of 2.6 m.y. was obtained from a basalt overlying Colorado River gravels at Grand Wash. Metzger and others (1973), consider the Bouse to be no older than this. It is an imprecise estimate and leaves room for considerable error. The apparent age range

and its lithology suggest that a minimum age could be better estimated by paleomagnetic studies.

Q1 is associated with Colorado River gravels although exact stratigraphic relations are not known. Bull (personal communication) has noted that older terrace gravels lack abundant basalt clasts, whereas younger ones contain them as a prominent component. The abundant basalt gravels in younger terraces may come from flows that dammed the Colorado River at Volcans Throne in the Grand Canyon. The oldest of these flows is about 1.2 m.y. old. Therefore, terraces lacking basalt might be older than this, and the associated Q1 likewise.

In the absence of better data, Q1 is considered to be between 2.5 and 1.2 m.y. in age. Its antiquity is attested to by the extreme cementation and degree of erosion.

The absolute age estimates of Q2 are based on radiometric dating. On the west side of the Coxcomb Mountains, California, Q2a sediments bury (or include) an ash correlated with the Bishop Tuff on the basis of its geochemical signature (Merriam and Bischoff, 1975; Fig. 5:5, Col. H). Dalrymple and others (1965) has dated the Bishop Tuff at 0.7 m.y. by K/Ar. Thus Q2a sediments and surfaces must be younger than this age. In the Vidal area, California, Ku and others (in preparation) have obtained four $^{230}Th/^{234}U$ ages on carbonate from Cca horizons of Q2a soils. Corrected ages range from 172,000$\pm$25,000 to 66,000$\pm$3,000 Y.B.P. and average 125,000. The youngest of these may be spurious since the other three are >125,000. It should be noted that the Th/U dates are best considered as estimates of minimum

age. First, since the material dated is pedogenic in origin, it post-dates deposition of sediment and possibly surface abandonment by streams, i.e., the age of pedogenesis probably represents time elapsed since surface stablization. Second, estimates of carbonate accretion on pebbles suggest mean rates of 1 mm/8,000 yrs. in this area. The above dates were obtained on the innermost 2 or 3 mm of pebble coatings which, therefore, may contain material spanning 16,000-24,000 years. Thus, the apparent age will be younger than true age. Regionally, it seems safe to say that Q2a ranges between 0.1 and 0.7 m.y. in age.

Q2b has been dated by $^{230}Th/^{234}U$ at 80,000 (Ku and others, in preparation). This is the mean of 15 samples from the Vidal area. Range is between 94,000 and 50,000 years B.P., and again the ages represent minimum age of the surface.

Q2c and Q3 have not been dated adequately. Q2c is regarded as Pleistocene on the basis of its soils and pavement development. A Th/U age of 61,000 $\pm$5,000 years was obtained by Ku and others (in preparation). The subdivisions of Q3 were spaced out at equal intervals between 10,000 and 2,000 years B.P. The 2,000 year maximum age of Q4 is established on the basis of lack of desert varnish. Roman-age ruins at Masada, Israel, dating from about 2,000 years ago have only incipient varnish on chert (Bull, in preparation, oral communication). Hunt and Mabey (1966) noted little or no varnish associated with artifacts of ceramic cultures in Death Valley, California. By analogy, the unvarnished Q4 should be younger than about 2,000 years B.P.

5.6.3 CLIMATIC SIGNIFICANCE AND INTERPRETATION

The subdivisions of Quaternary surfaces and their underlying fills can be recognized over much of southwestern Arizona and southeastern California. That such uniformity in sequence should be displayed over such a lithologically and structurally diverse area virtually demands an interpretation that emphasizes climate-controlled cycles of sedimentation and erosion. However, a brief glance at Fig. 5:5 shows no clear, systematic relation of alluvial units to climatically controlled glacial and lacustral sediments in Columns D and E. This may well result from the limited and imprecise chronologic data. Indeed, the only sound chronology is the interval between 8,500 B.P. and 33,000 B.P. for Searles Lake (Column E).

Focusing on the Pleistocene-Holocene boundary, certain trends are apparent. The Tioga Glaciation probably terminated prior to 10,000 B.P. and was followed by the Hilgard Glaciation that probably terminated by 9,000 B.P. The deglaciation was associated with a shift to warmer, dryer climate that resulted in desiccation of Searles Lake. The shift to warmer climate also initiated aggradation in the Colorado River floodplain. This trend of Holocene floodplain aggradation is also exhibited by the Rio Grande at Las Cruces, New Mexico (Hawley, 1975). On piedmonts, multiple phases of instability are indicated by three subunits of Q3.

The effects of the climate change on piedmont fluvial systems are indicated by contrasts in size and sorting between Q2 and Q3 sediments. Bull (1974, p. 64) proposed the following model:

> "The Holocene stratigraphy and landforms indicate the following adjustments in the fluvial systems--adjustments that started with the Pleistocene-Holocene

> climatic change. The drier, warmer climates of the earlier Holocene resulted in decreased vegetative density and increased sediment yields. Streamflow was unable to transport all the sediment and the valleys became choked with alluvium. Progressive decrease in soil thickness and increase in areas of bedrock outcrops operated as feedback mechanisms to further reduce soil cover and vegetative density and to increase runoff rates for a given rainfall event. The longitudinal profiles of the alluviating valleys steepened in response to increased sediment load and size. With increasing outcrop area runoff rates, the source of boulders increased and sediment yield decreased. Valley alluviation ceased and channel downcutting began when the streams were able to transport all of the diminished sediment yield and obtain additional load by erosion of the valley-fill deposits. Stream-channel downcutting (with concurrent decreases in gradient) have continued until now most streams are cutting into bedrock."

The model does not explain the manner in which stream systems responded to Pleistocene climate changes to deposit Q2 sediments. For instance, how Q2c fit in with the climate changes occurring during the Wisconsinan? The chronologic data available do not permit assignment to any of the three glacial advances occurring in the Sierra Nevada during this time interval.

One interesting point arises with Q2a sediments in the Coxcomb Mountains (Column H) and the Sherwin Till (Column D). The association of Q2a sediments above, and the Sherwin Till below, the Bishop Tuff might suggest that Q2a sediments were deposited in response to a shift to warmer, dryer climates in a manner similar to Q3 sediments. However, the Bishop Tuff provides only a limiting age, i.e., the Sherwin Till can be no younger and Q2a sediments can be no older. The two units may in fact be separated in time.

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6.0 INPUT AND MODIFICATION BY SOME EXTERNAL SYSTEMS by Ran Gerson

Two major external systems offset the quality of fluvially derived sediment:

1. Eolian, by mixing to total domination of the landscape.
2. Pedogenic, by translocation of fines, alteration, and precipitation of carbonates, sulphates and chlorides.

Both change previously coarser clastics into a mixture having smaller mean and poorer sorting. Their relative input may be from very insignificant, as in the case of actively moving fluvial sediments with respect to pedogenetic processes, to complete domination, as in the case in many sand and less blanketed depositional basins. Here much or all of the material may have been primarily or secondarily introduced by wind (Figure 6:1).

Some degree of stability of the landscape from degradation or transport by streams is necessary for effective introduction of fines and salts by wind and soil formation.

The most productive combination is large quantities of incoming dust (mainly silt sized) and a semiarid mode or effective soil formation. Such conditions occurred during the late Quaternary. Major addition of silts, formation of clays, and precipitation of eolian-introduced salts took place at that period (see Section 5.3).

While the erosional activity of the fluvial system decreases as the streams proceed into the depositional basin, the relative importance of external systems increases. A measure of this may be illustrated

Figure 6:1 The impact of primary and secondary eolian input in southwestern Arizona:

A. San Cristobal Valley

B. Arroyos in Growler Valley

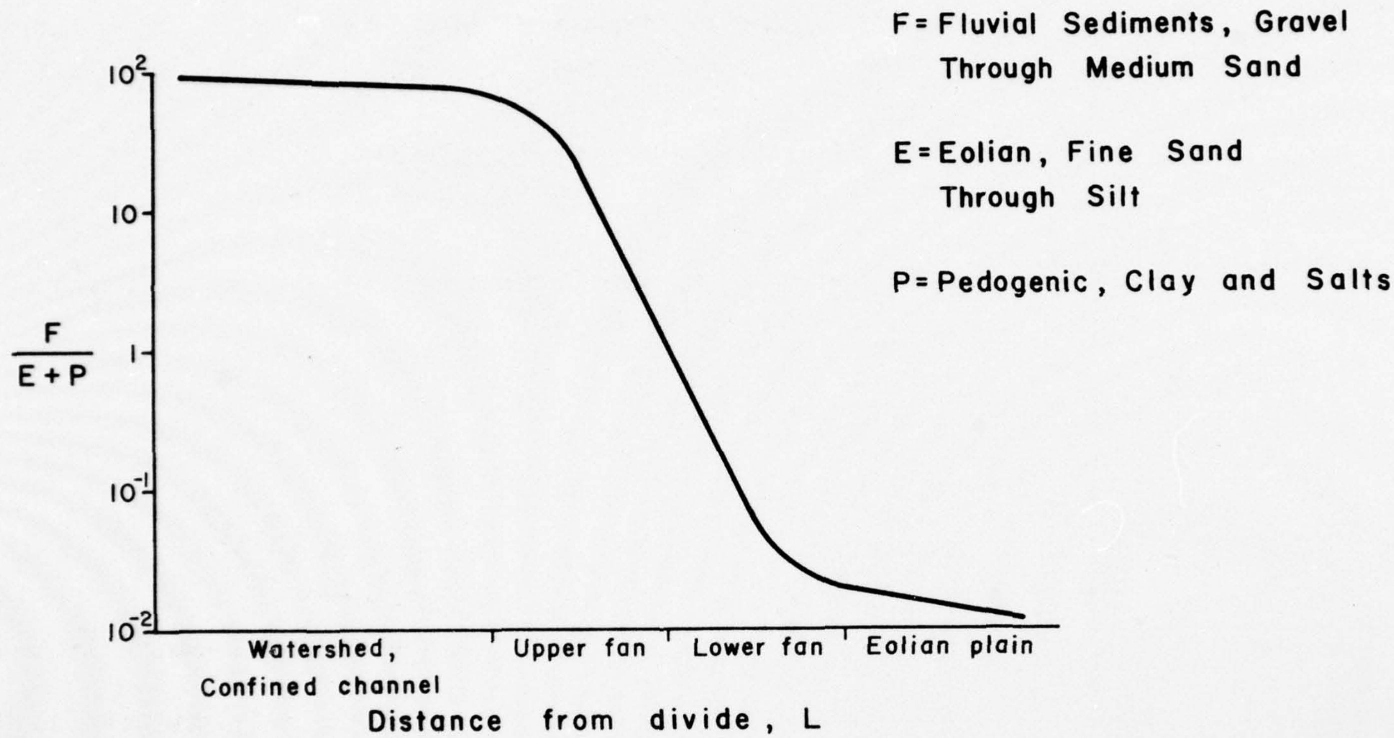

Figure 6:2 Trend of change of the ratio of fluvial vs. eolian and pedogenic inputs in a fluvial system.

by the change in the ratio of fluvial clastic to external fines in a depositional basin (Figure 6:2). An example of the actual ratio and the high addition of fines and salts is presented in Appendix E.

7.0 SUMMARY AND CONCLUSION by Ran Gerson

The present study is concerned with production, transport and deposition of gravel in fluvial systems in hot arid regions. It attempts a definition of the variables affecting gravel origin, transport and deposition, assessment of significant changes in texture after deposition and evaluation of the composition of gravel buried in the upper alluvial section of depositional basins.

The arid geomorphic environment is characterized by low precipitation, low rates of chemical weathering in most lithologic environments, high rates of mechanical weathering, scant vegetation and slow and sporadic soil development. General climate-process framework places most hot deserts in regions receiving less than 150 mm/yr of mean annual precipitation.

Major geomorphic processes and events, occurring in rocky deserts are: mechanical weathering; debris flows and wash on hillslopes; free wind activity; precipitation of salts in fractured and clastic rocks and soils, and floods.

Differential areal geomorphic activity and differential runoff - sediment contribution are very strongly emphasized in the arid environment.

Typical geomorphic zonation of the arid fluvial system is:

1. Mountainous watersheds.
2. Pediment-inselberg zone.
3. Depositional piedmont zone.

The thickness (T) of fluvial sediment over rock-cut pediments may be evaluated using surface slope (α), pediment length (L), characteristic of selected pediment angle (averaging 2.5^{o}): $T = L \tan 2.5^{o} - L^{2} \tan \alpha$.

Exposures of bedrock in pediments and inselbergs may assist in assigning boundaries to pediment-inselberg zone of shallowly buried bedrock. Rate of mountain front and hillslope retreat of frequently encountered cohesive rocks in arid environments is 10^{-2}-10^{-4} mm/yr.

The fluvial complex is an ecosystem in which the following groups of variables interact: climate, geology, vegetation, topography, hydrology, geomorphic processes, hydraulic geometry and sediment characteristics. Every group includes several variables. Many variables are measurable but several essential ones are not. For past sedimentary environments most variables cannot be reconstructed.

Floods in hot arid regions and their study may be characterized by several features:

1. Ephemeral, sporadic nature.
2. A wide range of magnitude of flow.
3. Unknown frequency of occurrence of floods of given magnitudes.
4. Steeply rising and falling hydrographs.
5. Highly differential areal contribution of runoff.
6. Fast infiltration of flood water into channel and fan alluvium.
7. Localized flood events due to spottiness of rainfall.
8. High variability in intensity, amounts and duration of flows.

Production of gravel is dependent on initial rock structure, rates of removal and weathering of rock and debris. Wash, debris flows and gullying are the main processes contributing debris to stream-channels.

Debris flow is the main process contributing large boulders to stream channels. In most hot arid environments they do not themselves transport coarse debris long distances. They occur mainly after a long period of talus formation and pedogenic processes contributing some fines.

The effects of lithology on production of debris is reflected both in particle size and sediment yield. Apart from rocks weathered to textural components, most cohesive rocks generate sediment yields related to structure - joint spacing and bed thickness. Joint density effects sediment size, talus accumulation, debris flow activity and sediment yield.

Among the frequency encountered igneous and metamorphic rocks, mainly coarse crystalline granites and quartz monzonites weather chemically to sand and granules. The most resistant are rhyolites and basalts. In the arid zone, there is no direct relationship between rock composition and erodibility or sediment size and yield.

There is an almost complete lack of empirical data related to water flow and sediment transport in arid watersheds. Nahal Yael and Sde Boker (southern Israel) experimental basins are the only ones in the truly arid environments in which rainfall, runoff and sediment relationship are empirically studied.

Of the various approaches to bedload transport in alluvial channels only the one relying on shear stress relationships may be applied to the poorly monitored desert streams. The stream power approach has proved successful once flow data are available. $D \propto \tau_c^{0.5}$ to $D \propto \tau_c^{1.0}$ is the wide range of particle size (D) - critical tractive force (τ_c) relationship.

The ratio between gravel and fines through a fluvial system changes with geological environment, space and time.

Rates of abrasion and decrease of size is dependent on rock resistance, work done and weathering during rest in the channel. Contribution from hillslope and terraces and selective transportation further determine the overall rate of change of size distribution downstream.

Changes in gravel size along arid fluvial systems cannot be correlated with dynamic variables, since these are not yet available for arid watersheds. Available data allow formulation of correlations between particle size variables and channel slope, distance from divide or drainage area. Correlation may assume the form of arithmetic, power or exponential functions, without a general mathematical low.

Five small watersheds in southwestern Arizona and southern California were studied. General trends in change of particle size parameters downstream are: mean particle size, sorting and maximum particle size are better correlated with channel slope than with distance from divide. Least degree of correlation is with drainage area. Coefficients of correlation of mean and maximum size with slope are .81-.99 and .17-.98, respectively. In larger watersheds, correlation is better than in small

ones, the former having higher stream power and longer flows for sediment-slope-flow adjustments. Stepwise multivariate analysis improve the correlations, slope being the first step and then distance.

Relatively low coefficients of correlation are obtained because of several reasons: lack of effectiveness of many flow events; duration of flow; the nature of floods; having steep hydrographs; superposition of sediments deposited in various flow events; sampling difficulties and representativeness in gravelly braided stream channels, sampled between floods; mixture with lag deposits of debris flows and high magnitude floods.

Very low correlation coefficients were found between particle size parameters and distance from divide and especially slope, in late Quaternary-early Holocene (Q_2) deposits. Here both sampling difficulties and morphometric representativeness lead to meaningless trends in relating sediment parameters to slope and distance variables.

There is no deviation in rate of change as alluvial fan zone is reached. This is due mainly to the active role played by medium to high magnitude flow events, in which abstraction of flow and meaningful changes in velocity and depth are not effective. Rates of change of particle size down-fan are similar to that in source watersheds.

Sediment transport and deposition are related to flow velocity, flow depth, channel slope and particle size. Decrease in the first three variables or increase of the last will cause deposition. While particle size decreases relatively slowly by abrasion, decrease of velocity, depth and slope occurs more rapidly once a stream enters an intramontane wide valley.

A characteristic depositional form in the depositional basin is the alluvial fan, which appears when the stream channel leaves the confinement of the valley slopes.

A mature fan area (A_f) is proportional to its source area (A_d): $A_f - CA_d^n$, where n ranges between 0.8 and 1.0. n was not found to be related to environmental factors while C is dependent on sediment yield or, indirectly, on lithology and jointing.

Empirically derived relationships of alluvial fans point at an inverse proportion of sediment yield to particle size. Less voluminous and/or smaller fans are associated with coarser sediment.

Boundaries of a mature fan may change because of several reasons: change in sediment yield and/or size following tectonic activity; change in sediment yield and/or size caused by climatic change; a general reduction of source watershed with time, affecting sediment yield and size. All these changes occur following a change in the runoff-sediment yield-sediment size relationships.

A characteristic difference is found between the wetter-mode late Quaternary sediments and drier-mode Holocene deposits. The former are finer, better sorted and extend further into the depositional basins than the latter. Late Holocene present-day alluvial fans are clearly smaller in size.

The effects of a high magnitude (extreme, "catastrophic") rainfall event in an arid terrain is limited in area (usually less than 25 km^2). Geomorphic expressions of intensive rainstorms are: debris flow on talus slopes, lateral and vertical scour of stream channels, transport of all available sized clastics,

from fines to large boulders. Most debris flow bouldery sediments are not transported more than 0.5 to 1.0 km downstream from mountain fronts. The larger debris flows in southwestern Arizona occurred in the early Holocene. Boulders moved exceed 2.0 m in size.

Quaternary and Holocene fluvial deposits have definite characteristics and some of them are readily identified as piedmont surfaces. Criteria for identification are surface morphology, sedimentology and degree of soil development. They are designated Q_1 (the oldest) through Q_4 (the youngest). Q_1 to Q_2 are Quaternary and Q_3 to Q_4 are Holocene in age. In most cases, they may be further subdivided.

Q_1 sediments are relatively thick (in some cases 40 to 70 m and more), poorly sorted, coarse gravelly sediments. They are intensively dissected and stripped of B soil horizons. Q_2 expose smooth, flat, surfaces, moderately dissected, with well-developed, varnished, desert pavement, over fine-grained, well-sorted gravel and well-developed soil profiles.

Soils of Q_2 surfaces usually have a vesicular silty A horizon, cambic or argillic B horizon and Cca lower horizon. Q_3 surfaces generally lack well-developed pavements, have bar and swale morphology, exposed abandoned braided pattern and have A-Cca soil profiles. Q_4 consists of active, present-day stream channels. Q_3 and Q_4 are generally coarser and less sorted than Q_2 sediments. Also, their extent is more limited. In many depositional basins, vast alluvial surfaces are built of Q_2 finer sediments and well-developed arid soils. Closer to the center of the depositional basin, where fluvial sediments are granule to silt materials, pedogenetic processes may have turned a large portion of the sedimentary sequence into a thick argillic B horizon, as is

the case of the MX Trench area in the San Cristobal Valley, southwestern Arizona.

Input of external systems into the fluvial deposits may be of different sources: eolian, pedogenic, groundwater and playa. All these may add fines (silts and clays) and salts (carbonates, sulphates and chlorides) to the fluvial sediments. The amounts added may very according to environmental conditions not related to the fluvial system itself and operate mostly subsequent to the deposition of fluvial clastics.

8.0 EVALUATION OF SIZE DISTRIBUTION OF SHALLOWLY BURIED FLUVIAL SEDIMENTS by Ran Gerson

8.1 GENERAL CONSIDERATIONS

Several practical considerations have to be taken into account dealing with prediction of buried fluvial sediments:

1. There are certain lithologic environments that yield smaller gravel sizes than others. These would be sandstones, coarse crystalline granites and quartz-monzonites (Figure 8:1), coarse crystalline basic rocks, such as dolerites and gabros. Most other rock types are more dependent on structure than composition and texture in their output of sediment yield.
2. Shattered rocks are prone to produce smaller sized gravels but induce higher sediment yields.
3. Effective drainage area decreases with age of tectonic terrain. Old, stable terrains are usually more pedimented and their contributing area is in practice smaller than the one deduced from map or imagery configuration.
4. There is a steady, though very fluctuating, decrease in gravel size (both mean and maximum), and increase in sorting downstream.
5. There is usually an increase of non-fluvial input of sand and silt into fluvial deposits downstream, especially within the depositional basin (Figure 6:2).
6. Late Quaternary deposits are generally smaller in particle size, better sorted and include higher amounts of fines than Holocene and present-day stream sediments. These fines are derived from both eolian origins and pedogenic processes, related to wetter modes of operation.

Figure 8:1 Quartz monzonitic terrains (Gila Mountains, southwestern Arizona).

A. Alluvial valley fill composed of sand, granules, and some gravel, next to talus hillslopes composed of coarse gravel.

B. Sandy stream channel next to coarse-gravel producing terrain. Gravel does not reach present-day alluvial fan.

7. Fossil debris-flow deposits in the upper portion of a fluvial system may indicate that some of these deposits are buried in the depositional basin.
8. Open-drainage networks in tectonically non-active terrains may be an indicator for continuous fluvial-eolian sedimentation in the central parts of a depositional basin, without any shallowly buried playa sediments.

8.2 REGIONAL SCREENING AND EVALUATION - INFORMATION FLOW

	In the present report	
	Included (chapter: section)	Excluded
REGIONAL		
Basin and Range Morphostructures	X (2.2)	
Climate: Arid	X (2.1)	
Non-arid		X
Tectonic activity	X (2.2)	
MOUNTAIN RANGE - DEPOSITIONAL BASIN		
Mountain front: Continuous mountain front	X (2.2,2.3)	
Discontinuous mountain front		X
Dominant lithology: Chemically weatherable	X (4.1.5)	
Mechanically weatherable	X (4.1.5)	
Pediment-inselberg zone	X (2.3)	
Evaluation of width	X (2.3)	
Exposure of rock cut pediments	X (2.3)	
Depth of rock cut pediments	X (2.3)	

	In the present report	
	Included (chapter: section)	Excluded
Depositional basin		
Evaluation of width and length		X
Evaluation of exposed gravelly/fine grained surfaces	X (5.0,6.0)	
Presence and evaluation of eolian plain		X
Presence and evaluation of playa deposits		X
FLUVIAL SEDIMENT SIZE EVALUATION		
Selection of transects		X
Sampling of Q_4 sediments	X (Appendix D)	
Measurements of distance from divide (using topographical maps) and slope (using topographical maps or clinometer in the field)		
Size analysis - mean, sorting, maximum	X (Appendix C,G)	
Regression of size parameters with slope and distance from divide	X (Appendix H, 4.2, 4.3)	
Extension of regression equation to buried fill, covered by eolian blanket, as ceiling curve for prediction	X (4.2, 4.3)	
Evaluation of possible inclusion of debris flow materials	X (4.1.3)	
Evaluation of external systems' effects: Addition, alteration	X (6.0)	
Refining/verification/rejection by geophysical methods		X

8.3 LIMITATIONS OF DATA AND METHODOLOGY

There are only few depositional environments where type of material may be readily predicted by assessment of rock type in the contributing watershed or source area. These areas of weatherable rocks, under most arid and

semiarid conditions: sandstones, coarse crystalline granites and quartz monzonites. Resulting are deposits of rocks weathered to textural components, sands and granules, respectively.

Most other rocks weather to larger than textural components size fractions. Resulting clastics may range, according to joint spacing, talus evolution, debris flow activity and streamflow characteristics, between boulder and sand sizes.

In most Basin and Range fluvial systems of the southwestern United States and similar terrains there is no general controlling environmental factor or combination of factors that allow prediction of sediment size distribution without field investigation. Exceptions are the above mentioned lithologic environments, distance from divide and channel (or fan) slope, factors which represent decrease in sediment size and increase of sediment sorting as they increase or decrease, respectively.

To a certain extent, two other temporal and spatial factors may help in evaluation of trends in sediment size:

1. Climatic change.
2. Tectonic activity.

The first (see Chapter 5) may help in assessment of relative amounts of gravel, according to climatically determined mode of operation. The second may help in determination of relative amounts of gravel input, being greater in tectonically active terrains (see Section 2.2.3).

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The presence of clastic sediment of a given size distribution at a given point is dependent on too many variables, many of which cannot be measured or quantified (see Section 3.1 and Figure 3:1). This is especially true for fluvial clastics deposited during the late Quaternary and the Holocene.

In long-term, tectonically non-active terrains, an assumption may be made that the present geomorphic zonation is an approximation for the recent geologic past. This working assumption should take into account the following trends:

1. Gravel in Q_2 sediments may be present further from the mountain front than other Q_1 gravel, but Q_2 gravel are usually finer in size (see Chapter 5 and Section 4.3.2).
2. Q_2 sediments in the center of a depositional basin may include large quantities of pedogenetic silts, clays and salts (Appendix E and Chapter 6).

Extension of existing regression equations relating sediment size characteristics to distance from divide and slope is the only way to extrapolate or project from observed and measured material. This method, although unconventional, is the only one to arrive at a ceiling grain size distribution for buried fluvial deposits related to a known sedimentary unit. The actual sediment should be finer than predicted by the extrapolation because of drop of size at the toes of alluvial fans and mixture with finer materials winnowed from upper reaches of the fluvial system and addition of eolian and pedogenetic fines (Figure 8:2).

Evaluation of buried materials may be done in a less exhausting way by field inspection of exposed deposits and using the observations as ceiling size characteristics for deposits down-system, without quantitative treatment.

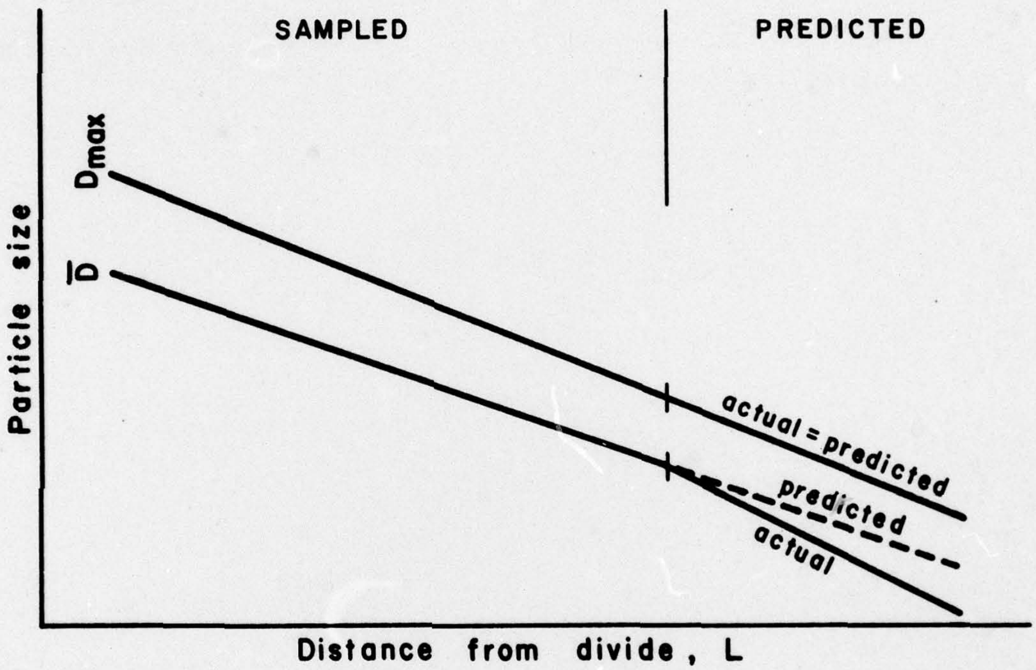

Figure 8:2 Actual and predicted decrease of gravel particle size.